

**TP 13518E**

**Tank-Car Insulation Defect Assessment Criteria:  
Thermal Analysis of Defects**

**for**

**Transport Canada  
Transportation Development Centre**

**by**

**A. M. Birk Engineering  
Kingston, Ontario, Canada**

**October 1999**

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## Notices

This report reflects the views of the authors and not necessarily those of the Transportation Development Centre.

The Transportation Development Centre does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

The Report uses the term "defect" when addressing any level of thermal protection and insulation deficiency. The term "defect" as used in this Report is not intended to define a level of non compliance with Regulations or Standards but rather a deteriorated or degraded condition which is not yet established as constituting an unacceptable or out of Standard situation.

Un sommaire français se trouve avant la table des matières.



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16. Abstract <p>An inspection technique was previously developed to find thermal insulation deficiencies on rail tank-cars. This method uses a thermal imager to locate insulation gaps under the tank steel jacket, relying on a small temperature difference between the tank lading and the surroundings. Limited field tests suggest that some tanks may have insulation deficiencies, which raises the question as to whether these deficiencies are important from a safety standpoint.</p> <p>This report contains an analysis using rail tank-car thermal computer models to show how insulation defects affect the tank thermal response to the environment and fire impingement. The objective of this work was to develop criteria for assessing insulation defects on tank-cars with thermal protection or with thermal insulation. These assessment criteria will be used by inspectors to decide when a tank will need insulation repairs. The analysis of thermally protected tanks was conducted using an approach similar to the U.S. Federal Railroad Administration (FRA) computer code Analysis of Fire Effects on Tank Cars (AFFTAC 3.0). All analysis used CAN/CGSB 43.147-97 as the applicable standard.</p>				
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## Executive Summary

Certain rail tank-cars require thermal insulation to protect them from accidental fire impingement (these systems are referred to as *thermal protection systems*), while others have insulation to keep the tank commodity thermally insulated from the surroundings (these systems are referred to as *thermal insulation systems*). In both cases, it is possible to have insulation defects that can reduce the effectiveness of the system.

A new inspection technique was developed by A.M. Birk Engineering to find thermal insulation deficiencies on rail tank-cars. This method uses a thermal imager to find insulation gaps under the tank steel jacket. The method relies on a small temperature difference existing between the tank lading and the surroundings. Solar heating can also assist in generating thermal gradients that the thermal imager can identify. Further details of this system can be found in the 1998 Transportation Development Centre report entitled *Thermographic Inspection of Tank-Car Thermal Insulation*, TP 13203E.

Limited field tests suggest that some tanks have insulation deficiencies. A few older tanks have been inspected and were found to be over 50 percent defective. However, are these deficiencies important from a safety standpoint? The objective of this work was to develop criteria for assessing insulation defects on tank-cars with thermal protection or thermal insulation. These criteria will be used by inspectors to decide when a tank will need insulation repairs.

This report contains details on an analysis using rail tank-car thermal computer models to show how insulation defects affect the tank thermal response to the environment and fire impingement. The analysis presented in this report was conducted to quantify what level of defect is acceptable. This analysis was based on the CAN/CGSB 43.147-97 standard that specifies insulation system performance.

### ***Thermally Protected Tanks***

A computer model was developed to represent a thermally protected tank-car with insulation defects exposed to engulfing and torch type fires. This model, called Tank Model with Insulation Defects (TMID), is based for the most part on assumptions similar to those of the U.S. Federal Railroad Administration (FRA) Analysis of Fire Effects on Tank Cars (AFFTAC) computer code.

The TMID model is two-dimensional in that it represents the tank as a long cylinder. Insulation defects are modelled as regions where no insulation exists between the steel jacket and the tank wall. Defects are assumed to run the entire tank length on one side of the tank. Defect position is specified by giving the angle from the tank top to the defect top and bottom.

The baseline case considered the following type of tank and assumptions:

- 112J340W propane tank
- tank diameter: 3 m, length: 17.3 m
- wall thickness: 17.5 mm
- insulation conductance: 22.7 W/m<sup>2</sup>K
- insulation thickness: 13 mm
- initial fill: 90 percent
- initial temperature: 15.6°C
- PRV assumed to hold tank pressure at maximum of 1.03 x start to discharge pressure
- PRV start to discharge pressure: 1.93 MPa) (280.5 psig)
- PRV capacity assumed large enough to maintain assumed pressure
- tank material: TC 128 steel

Based on the above tank, the AFFTAC model showed that:

- current thermal protection systems are more than adequate to protect a tank for 100 minutes from an engulfing fire with an effective radiating temperature of 816°C.
- current thermal protection systems are more than adequate to protect a tank for 30 minutes from a torching fire with an effective radiating temperature of 1204°C, and an effective torch emissivity of 0.536.
- the simulations suggest that the pool fire test is the determining test. However, this conclusion changes if the torch properties are adjusted to more accurately represent a credible torch fire accident.

Both the AFFTAC and TMID models showed that large defects can bring a tank to failure under engulfing fire conditions as defined by the CGSB standard within 100 minutes.

Based on the TMID model:

- it was concluded that a factor of safety (FOS) should be applied in this analysis. In the case of thermal protection, the FOS is defined in this report as (tank burst pressure at 100 minutes in fire)/(tank pressure at 100 minutes in fire). The current insulation systems with no defects have FOS > 3.0. Based on uncertainties of PRV performance, fire heating, and high temperature steel properties, it was suggested that an FOS = 1.6 would be reasonable.
- when an FOS of FOS = 1.6 is used, a 112 tank with propane exposed to fire for 100 minutes can have between 4 to 24 percent defective insulation provided a steel jacket is present and is not in direct contact with the tank primary wall. The 24 percent end of the range assumes the remainder of the tank is protected with



perfect insulation with properties as quoted for Kaowool ceramic blanket with 72 kg/m<sup>3</sup> density. The 4 percent end of the range assumes that the remainder of the tank is protected with insulation with a conductance of 22.7 W/m<sup>2</sup>K, which represents the maximum conductance that would pass the FRA plate test standard (i.e. keep steel plate sample temperature below 427°C for 100 minutes when exposed to a pool fire).

- the allowable defect area was strongly affected by input variables including:
  - assumed FOS
  - wall thickness
  - PRV setting
  - tank fill
  - fire temperature
  - commodity
  - tank surface emissivity
- detailed analysis of defects suggested that:
  - as defect gets small the wall stress and temperature may be reduced
  - several small well separated defects are safer than one large defect
- defects in the vapour space are more significant than those in the liquid space. However, the possibility of tank rollover makes this difficult to apply in the field.

The above conclusions have come from computer simulation results and, therefore, are not fully validated. It is recommended that some testing be conducted to confirm these results.

### ***Thermally Insulated Tanks***

A computer model was developed to calculate the effects of insulation defects on the overall conductance of thermally insulated tanks. For insulated tanks, the following conclusions have been made.

- Current non-defective thermal insulation systems with no insulation discontinuities just meet the required conductance, as specified in CAN/CGSB 43.147-97. Analysis suggests that less than 2 percent of the tank surface could have insulation defects and still meet the requirement. However, if existing insulation discontinuities are accounted for, no defects would be allowed.
- Some commodities, such as chlorine, cannot tolerate high temperatures (i.e. chlorine will cause steel to ignite at temperatures above 215°C). Therefore, some commodities cannot tolerate any insulation defects.
- Further analysis is necessary to properly quantify allowable insulation defects.



## Sommaire

Certains wagons-citernes doivent comporter une isolation thermique pour les protéger contre l'effet des flammes en cas d'accident (il s'agit de wagons-citernes à *protection thermique*) alors que d'autres ont une isolation thermique destinée à soustraire leur contenu à la température ambiante (wagons-citernes dits *isothermes*). Dans les deux cas, des défauts d'isolation peuvent apparaître avec pour effet une protection réduite du wagon ou de son contenu.

La société A.M. Birk Engineering a mis au point une nouvelle technique d'inspection pour déceler les défauts d'isolation des wagons-citernes. Elle fait appel à un imageur thermique qui repère sous la jaquette en acier des citernes les endroits où l'isolant est détérioré ou totalement absent. Cet appareil repose sur le principe de la détection des légères différences de température entre le contenu de la citerne et le milieu ambiant. Il a été établi également que les conditions ensoleillées sont de nature à engendrer des gradients thermiques détectables par l'imageur thermique. On trouvera plus de détails sur cet appareil dans le rapport TP 13203E intitulé *Thermographic Inspection of Tank-Car Thermal Insulation*, fait pour le Centre de développement des transports en 1998.

Des essais limités sur le terrain indiquent que certaines citernes peuvent effectivement comporter des défauts d'isolation. À l'inspection de quelques wagons-citernes anciens, il a été établi que leur isolation thermique était à plus de 50 p. cent défectueuse. Toutefois, on ne sait pas si cette situation compromet sérieusement la sécurité. La présente recherche avait pour objet de développer des critères d'évaluation des défauts d'isolation des wagons-citernes à protection thermique et des wagons-citernes isothermes. Les inspecteurs se serviront de ces critères pour décider si la protection ou l'isolation thermique d'un wagon a besoin d'être réparée.

Ce rapport présente une simulation informatique du comportement au feu et de la réaction à la température ambiante de wagons-citernes comportant des défauts d'isolation. Cette simulation avait pour objet de déterminer le degré de détérioration acceptable de la protection ou de l'isolation thermiques. Toutes les évaluations ont été faites par rapport aux exigences de performance d'isolation de la norme CAN/CGSB 43.147-97.

### ***Wagons-citernes à protection thermique***

Un modèle informatique a été élaboré pour simuler le comportement au feu d'un wagon-citerne présentant des défauts d'isolation thermique et enveloppé de flammes ou soumis à un jet de gaz enflammé. Ce modèle, baptisé Tank Model with Insulation Defects (TMID), applique pour la plus grande part des hypothèses proches de celles retenues pour le modèle informatique AFFTAC 3.0 (Analysis of Fire Effects on Tank Cars) de la U.S. Federal Railroad Administration (FRA).



Le modèle TMID est du type bidimensionnel du fait qu'il représente le wagon comme un long cylindre. Les défauts d'isolation pris en compte dans la simulation prennent la forme de zones où il ne subsiste aucun isolant entre la jaquette en acier de la citerne et la citerne elle-même. Il est posé que ce défaut s'étend d'un côté sur toute la longueur de la citerne. Sa position verticale est définie par l'angle formé par deux droites reliant ses limites supérieure et inférieure au sommet de la citerne.

La modélisation de référence avait pour objet le wagon ci-dessous et posait les hypothèses suivantes :

- wagon-citerne à propane 112J340W
- diamètre citerne : 3 m; longueur : 17,3 m
- épaisseur de paroi : 17,5 mm
- conductance thermique de l'isolant :  $22,7 \text{ W/m}^2\text{K}$
- épaisseur de l'isolant : 13 mm
- remplissage initial de la citerne : 90 p. cent
- température initiale :  $15,6^\circ\text{C}$
- la soupape de sûreté est présumée maintenir dans la citerne une pression maximale de 1,03 fois sa pression nominale d'ouverture
- pression d'ouverture de la soupape de sûreté : 1,93 MPa (280,5 lb/po<sup>2</sup>)
- la soupape de sûreté est présumée avoir une capacité d'écoulement suffisante pour maintenir la pression à l'intérieur de la citerne à la valeur présumée
- citerne en acier TC 128

Selon les simulations AFFTAC appliquées au cas de référence ci-dessus :

- les protections thermiques actuelles suffisent largement pour protéger pendant 100 minutes une citerne des effets d'un bain de flammes ayant une température effective de rayonnement de  $816^\circ\text{C}$ .
- les protections thermiques actuelles suffisent largement pour protéger pendant 30 minutes une citerne des effets d'un jet de gaz enflammé dont la température effective de rayonnement atteint  $1\,204^\circ\text{C}$  et l'émissivité 0,536.
- l'essai déterminant est celui en bain de flammes enveloppantes. Par contre, lorsque les propriétés du jet de gaz enflammé sont modifiées pour représenter plus fidèlement les conditions d'un accident provoquant un jet de gaz enflammé, cette conclusion change.

Les deux modèles AFFTAC et TMID montrent que des défauts d'isolation étendus peuvent entraîner en moins de 100 minutes la rupture d'une citerne plongée dans un bain de flammes ayant les caractéristiques définies dans la norme CAN/CGSB 43.147-97.

Selon la simulation TMID :

- il faut appliquer un facteur de sécurité (FS) dans cette analyse. Dans le cas d'une citerne à protection thermique, ce facteur est défini comme suit dans le rapport : (pression de rupture après 100 minutes dans les flammes)/(pression interne de la citerne après 100 minutes dans les flammes). Les systèmes isolants actuels exempts de défaut ont un facteur de sécurité supérieur à 3. Compte tenu des incertitudes concernant la performance des soupapes de sûreté, les températures en jeu et les propriétés des aciers haute température, un facteur de sécurité de 1,6 semblerait raisonnable.
- avec un facteur de sécurité de 1,6, une citerne à propane de type 112 exposée aux flammes pendant 100 minutes peut présenter un défaut d'isolation couvrant entre 4 et 24 p. cent de la surface totale de la citerne dans la mesure où celle-ci est entourée d'une jaquette en acier sans contact direct aucun avec sa paroi. La valeur admissible supérieure (24 p. cent) suppose que le reste de l'isolant est en parfait état et assure la protection thermique d'une doublure céramique Kaowool (masse volumique de  $72 \text{ kg/m}^3$ ). La valeur admissible inférieure (4 p. cent) vaut pour les cas où l'isolant de protection a une conductance de  $22,7 \text{ W/m}^2\text{K}$ , soit la conductance maximale permettant de réussir à l'essai standard de résistance de la FRA (maintenir la température de l'éprouvette sous  $427^\circ\text{C}$  pendant 100 minutes d'exposition à un bain de flammes enveloppantes).
- l'étendue admissible du défaut variait considérablement selon la valeur attribuée aux variables de la modélisation :
  - FS présumé
  - épaisseur de paroi
  - pression d'ouverture de la soupape de sûreté
  - niveau de remplissage de la citerne
  - température des flammes
  - produit transporté
  - émissivité pariétale de la citerne
- l'analyse détaillée des défauts laisse penser que :
  - moins le défaut est étendu moins la paroi de la citerne risque d'être sollicitée et réchauffée
  - plusieurs petits défauts bien séparés présentent moins de risques qu'un seul défaut de grande superficie
- les défauts d'isolation au-dessus de la marge de remplissage ont plus de conséquences que ceux donnant au-dessous de cette marge. Cette conclusion ne vaut cependant plus dès qu'il y a eu renversement du wagon-citerne.

Les conclusions ci-dessus sont fondées sur les seuls résultats de simulations informatiques; elles sont donc sujettes à caution. Aussi, est-il recommandé de mener certains essais de validation.

### ***Réservoirs isothermes***

Un modèle informatique a été élaboré pour calculer les effets des défauts d'isolation sur la conductance globale des citernes isothermes. Voici les conclusions tirées de la simulation :

- Les systèmes d'isolation actuels en parfait état qui couvrent intégralement la surface intérieure de la citerne offrent tout juste l'isolation prescrite, en termes de conductance, par la norme CAN/CGSB 43.147-97. L'analyse suggère qu'une citerne ayant un défaut d'isolation sur moins de 2 p. cent de sa surface totale offrira encore l'isolation thermique prescrite. Par contre, avec une isolation non intégrale aucun défaut d'isolation ne serait admissible.
- Certains produits tels que le chlore n'admettent aucune élévation marquée de la température. Le chlore, en l'occurrence, rend l'acier combustible dès que la température dépasse 215 °C. Les citernes servant à transporter de tels produits ne peuvent présenter aucun défaut d'isolation.
- D'autres analyses sont nécessaires pour bien quantifier l'étendue admissible des défauts d'isolation.

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# **1 Introduction**

## **1.1 Background**

An inspection technique was developed by A. M. Birk Engineering to find thermal insulation deficiencies on rail tank-cars. This method uses a thermal imager to find insulation gaps under the tank steel jacket. The method relies on a small temperature difference existing between the tank lading and the surroundings. Also, solar heating can assist in the generation of thermal gradients that the thermal imager can identify. Further details of this system can be found in the Transportation Development Centre report "Thermographic Inspection of Tank-Car Thermal Insulation", TP 13203E, dated March 1998.

Limited field tests suggest that significant numbers of tanks may have insulation deficiencies. Now the question must be asked – are these deficiencies important from a safety standpoint?

This report contains an analysis using rail tank-car thermal computer models to show how insulation defects affect the tank thermal response to the environment and fire impingement.

## **1.2 Objectives and Scope**

The objective of this work was to develop criteria for assessing insulation defects on tank-cars with thermal protection or with thermal insulation. This assessment criteria will be used by inspectors to decide when a tank will need insulation repairs.

As requested by Transport Canada, the analysis of thermally protected tanks was to be conducted using an approach similar to the US Federal Railroad Administration (FRA) computer code AFFTAC 3.0.

All analysis was to use CAN/CGSB 43.147-97 as the applicable standard.



## 2 Tank Insulation Systems

The system considered in this report is shown in Figure 2-1. It consists of a horizontal cylindrical pressure vessel covered with a layer of thermal insulation with a steel jacket cover over the insulation. In this report, two different tank-car insulation systems will be considered – thermal protection and thermal insulation.

### 2.1 Thermal Protection Systems

Thermal protection systems are designed to protect tanks from accidental fire exposure. These systems were introduced in the late 1970's and early 1980's as a result of an extensive research program to identify ways of reducing tank-car accidents.

#### 2.1.1 Requirements for Pressure Cars with Thermal Protection

The requirement for thermal protection systems for pressure tank-cars is specified in CGSB 79.18 (see Appendix A, Appendix B). Basically the requirement is:

*thermal protection on a tank car, shall have sufficient thermal resistance so that there will be no release of any lading from within the tank car, except release through the pressure relief device, when subjected to:*

- (1) A pool fire for 100 min, and
- (2) A torch fire for 30 min.

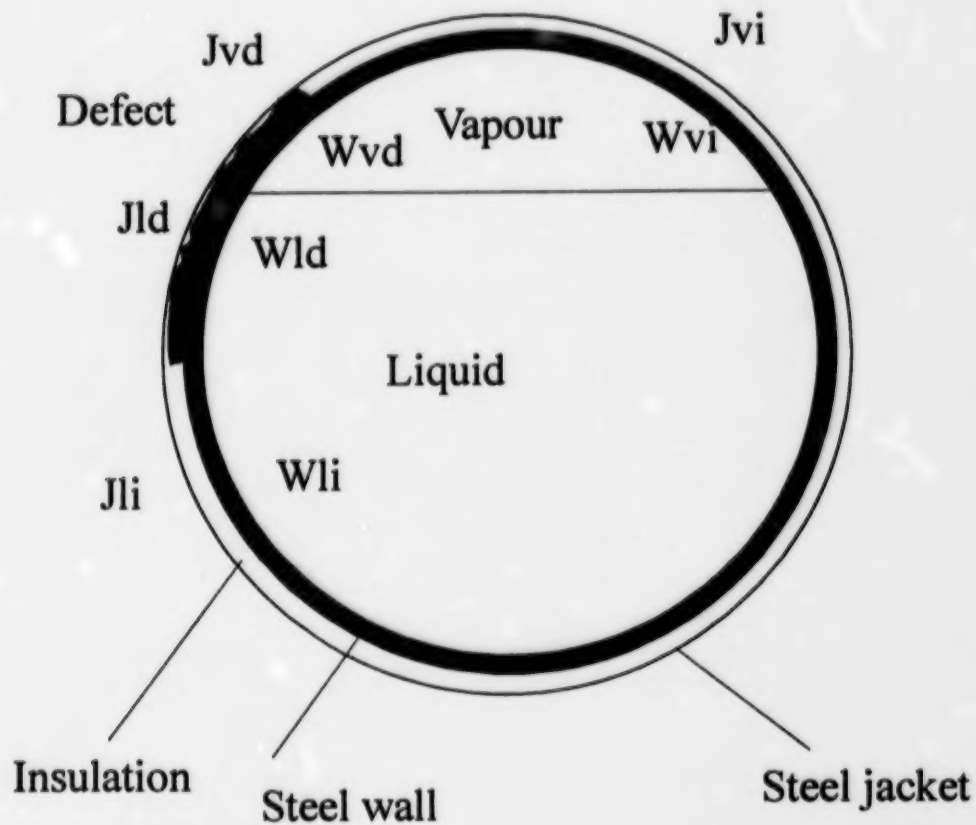
This specification is a change from a previous standard that involved a fire test of a steel plate sample covered with insulation. However, the older standard pass/fail criteria was not plate failure but rather a measured temperature of 427 °C within the time allowed (i.e. with pool fire plate temperature must stay under 427 °C for 100 minutes, for torch fire plate temperature must stay under 427 °C for 30 minutes). To pass the old requirement an insulating material had to have an overall conductance of less than 22.7 W/m<sup>2</sup>K (4 Btu/hr ft<sup>2</sup> °F) (see Johnson (1998)).

The DOT standard pool fire must have a temperature of 871° C plus or minus 56° C. As per the CGSB plate test standard, the engulfing pool fire must heat a 16 mm steel plate to 427° C within 13 min (plus or minus 30 seconds). This time requirement is based on the full scale fire test of a tank-car (Townsend et al (1974)).

#### 2.1.2 Effect of Thermal Protection

Thermal protection reduces the rate of heat addition to the tank. This means the tank will heat up more slowly and it will take longer to empty through the pressure relief

valve (PRV). If a thermally protected tank has insulation defects then the increase in heating rate will cause the tank to empty more rapidly through the PRV. Where there are



Jvd - jacket vapour defect  
 Jvi - jacket vapour insulated  
 Jld - jacket liquid defect  
 Jli - jacket liquid insulated  
 Wvd - wall vapour defect  
 Wvi - wall vapour insulated  
 Wld - wall liquid defect  
 Wli - wall liquid insulated

**Figure 2-1: Sketch Showing Insulation System with Defect**

gaps in the thermal insulation, vapour space wall temperatures will be higher than in places where there is intact thermal insulation.

If a tank is protected just enough to pass the pool fire requirement, then theoretically any defect will make it fail. If a tank exceeds the requirement by say 10%, then defects would be acceptable, until this 10% margin is lost.

A 112 type tank-car with no thermal protection was exposed to an engulfing JP4 fueled pool fire in the early 1970's and it failed after about 24 minutes (see Townsend et al (1974). Had it not failed it would have emptied through its relief valve in about 40 minutes. A thermally protected tank must survive a pool fire for 100 minutes without failing (i.e. releasing its contents other than through the pressure relief valve).

A 112 type tank car with just a steel jacket (no thermal insulation in the gap) has some thermal protection from the steel jacket because the jacket behaves like a thermal radiation shield (see Birk (1983)) and this reduces the heat flow by about half. With steel jacket alone a tank exposed to an engulfing pool fire will empty after about 85 minutes. If the fire is severe enough it may fail before it is empty. Once it is empty of liquid, the tank lading and wall temperatures may continue to rise and if the tank pressure is not reduced the tank could fail.

A 112 type tank car with 13 mm of high temperature thermal insulation (such as Kaowool – see Appendix F) covered with steel jacket will survive a pool fire for well over 100 minutes. Further details of this will be presented later in this report. The idea being studied here is that, if the tank exceeds the requirements of the pool fire test then it should be acceptable to have some insulation defects.

## **2.2 Thermal Insulation**

Thermal insulation is generally used for tanks that carry commodities that must be thermally insulated from the surroundings. Insulation may or may not be a tank specification requirement. This thermal insulation will keep the commodity warm or cool relative to the surroundings. Some tanks that require thermal insulation may also require thermal protection.

### **2.2.1 Requirements for Thermal Insulation of Pressure Tank-Cars**

In general, if a pressure tank-car requires thermal insulation it must meet the following requirement:

*If insulation is a specification requirement, it shall be of sufficient thickness so that the thermal conductance at 15.5 °C (60 °F) is not more than 1.533 kJ/h·m<sup>2</sup>·°C (0.075*

*Btu/h·ft<sup>2</sup>·°F) temperature differential. If exterior heaters are attached to the tank, the thickness of the insulation over each heater element may be reduced to one-half that required for the shell.*

It should be noted that for some commodities (for example CO<sub>2</sub>) the thermal conductance must be even lower.

For tanks that need both thermal insulation and thermal protection, it can be seen this requirement of a conductance of 0.075 far exceeds (by about a factor of 50, if we use 4 Btu/hr ft<sup>2</sup> F as the limit to pass the thermal protection requirement) that needed for the thermal protection requirement. However, for the insulation to pass the thermal protection requirement it must be a high temperature insulation.

Common insulation systems include 5 cm of fibreglass insulation (low temperature) and 5 cm of ceramic blanket (high temperature insulation).

### **2.3 Insulation Discontinuities**

One issue that has not been discussed so far is insulation discontinuities that exist in a normal tank-car. These discontinuities are direct metal conduction paths that are present due to tank design features.

Discontinuities and associated U values were suggested by Johnson (1998) in the AFTAC 3.0 manual. This data is shown in **Table 2-1**. It is not clear how these U values were obtained or whether they assume a certain convective film coefficient on the tank outer and inner surface. For now it has been assumed that these U values are based only on thermal conductivities of the tank wall materials.

As can be seen from the table the discontinuities are not very significant for a thermally protected tank with 13 mm of insulation (insulation discontinuities increase overall U by 1%). In this case discontinuities will be ignored.

However, discontinuities are significant for thermally insulated tank where the overall wall U coefficient is increased by 43%. This result is somewhat misleading because the 43% increase represents a small overall increase in heat transfer when compared to what a large insulation defect would produce.

Let us consider a 1 m x 1 m portion of the tank with steel jacket but all the insulation is removed. The U value for this area depends on the heat transfer conditions. Table 2-3 shows a summary of the U value associated with this 1 square meter of defect.

The U value for the wall area with insulation is calculated from the following expression :

Table 2-1: Summary of Insulation Discontinuity U values (from Johnson (1995))

location	U (BTU/hr °F)	U (W/K)
manway nozzle and cover	14.6	2.4
siphon and air vent nozzle	6.1	1.0
safety relief valve nozzle	3.2	0.52
jacket spacers	15.5	2.5
bottom outlet saddle	13.1	2.1
draft sills	72.9	11.9
body bolsters	65	10.6
brake cylinder support	4.6	0.75
brake rod lever support	3.2	0.52
total U for discontinuities (sum of individual U's)	198.2	32.3
total U for thermally insulated tank (105 car assuming conductance of 0.426 W/m <sup>2</sup> K)	456	74.3
total U for thermally protected tank (112 car assuming conductance of 22.7 W/m <sup>2</sup> K)	24300	3960

1 Btu/hr °R = 0.163 W/K

$$U = \frac{1}{R} = \frac{1}{\frac{1}{h_{outside}} + \frac{w_{wall}}{k_{wall}} + \frac{w_{insul}}{k_{insul}} + \frac{1}{h_{inside}}}$$

where,

w = wall or insulation thickness

k = thermal conductivity (W/mK)

h = convective heat transfer coefficient (W/m<sup>2</sup>K)

The resulting U value depends on the insulating properties of the insulation and also on the convective coefficients. On the tank inside surface it is reasonable to assume the h is large if the wall is wetted by liquid. However, on the outside the h value depends on the ambient conditions. Table 2-2 shows some typical convective heat transfer coefficients for a wind blowing over a cylinder. At low wind speeds the convective coefficient is quite low and this can reduce the overall U value for a tank significantly (i.e. the outside h become a resistance to heat flow).

**Table 2-2: Convective Film Coefficient for Wind Blowing over Tank-Car**

Wind Speed (km/hr)	h (W/m <sup>2</sup> K)
3	3
6	6
16	12
32	21

The U value for the wall area with no insulation present must include thermal radiation in from the jacket to the wall where the insulation is gone. Table 2-3 shows how the tank U value is affected by the discontinuities and by defects.

As can be seen from the table, the importance of insulation defects and discontinuities depends on the specific heat transfer conditions. This is because the outside surface convective coefficient is itself a barrier to heat transfer. A change in the outside h will also change the overall U for the tank system. As the temperature of the exterior heat source increases thermal radiation takes over as the dominant mode of heat transfer. This change in temperature also changes the overall U value.

The results show that 1 m<sup>2</sup> of defect can be more important than all the discontinuities. The worst case defect is when the insulation is gone and the steel jacket is put in direct contact with the tank wall. One square metre of such a defect is more important than the tank discontinuities.

If an air space is left where there is no insulation then the U value depends on the temperature difference. As can be seen, a 1 m x 1 m defect becomes just as important as all the insulation discontinuities as soon as the heat source temperature exceeds the lading temperature by 600 degrees. However, at ambient temperatures (say 100 °C difference) it takes between 3 and 5 m<sup>2</sup> of defect to equal the effect of the insulation discontinuities

From this point on, insulation discontinuities will not be discussed.



**Table 2-3: Summary of U Value for 1 m x 1 m Insulation Defect (assuming  $h = 5 \text{ W/m}^2\text{K}$  in the annulus if no insulation is present)**

	Thermal Insulation 102 mm nominal conductance $0.426 \text{ W/m}^2 \text{ K}$		Thermal Protection 13 mm insulation nominal conductance $22.7 \text{ W/m}^2 \text{ K}$	
approximate tank U with no defects or discontinuities (outside $h = 50 \text{ W/m}^2\text{K}$ )	74 W/K		2700 W/K	
approximate tank U with no defects or discontinuities (outside $h = 5 \text{ W/m}^2\text{K}$ )	69		715 W/K	
increase in U of tank due to discontinuities (from Johnston (1998)) $h$ outside not specified	32.3		32.3	
increase in U for $1 \text{ m}^2$ steel jacket in direct contact with tank shell ( $h$ outside = $50 \text{ W/m}^2\text{K}$ )	48 W/K		48 W/K	
increase in U for $1 \text{ m}^2$ steel jacket in direct contact with tank shell ( $h$ outside = $5 \text{ W/m}^2\text{K}$ )	5.0		5.0	
increase in tank U for $1 \text{ m}^2$ defect (no insulation) including thermal radiation vs temperature difference				
	$h$ outside = $50 \text{ W/m}^2\text{K}$	$h$ outside = $5 \text{ W/m}^2\text{K}$	$h$ outside = $50 \text{ W/m}^2\text{K}$	$h$ outside = $5 \text{ W/m}^2\text{K}$
with $1^\circ\text{C}$ temp difference between surroundings and liquid lading	8.2 W/K for $1 \text{ m}^2$ surface	4.9	8.2 W/K for $1 \text{ m}^2$ surface	4.9
$10^\circ\text{C}$ difference	8.3	5.1	8.3	5.1
100	10	6.5	10	6.5
200	13	8.8	13	8.8
400	20	16	20	16
500	25	21	25	21
600	32	28	32	28
800	49	45	49	45

note: all surfaces assumed to have emissivity of 0.9

## **2.4 Defect Assessment Criteria**

In this work it is necessary to consider insulation defects and to determine whether these defects are severe enough to require repair. The test criteria will be the CGSB specifications for tank-car thermal insulation and thermal protection.

Computer models were used to simulate heat transfer conditions in a tank-car with thermal insulation defects. These models are based on good engineering principles and where there is some uncertainty in methods, the methods as described in the AAR document SD-053 (TCFIRE: A Model for Prediction of Fire Effects on Tank Cars) will be used. It should be noted that the computer program once called TCFIRE is now called AFTTAC.

The following sections briefly describe the assessment criteria for the insulation defects.

## **2.5 Commodities and Tank Types**

In this report we wish to analyse the impact of insulation defects on tank-cars that carry dangerous goods. The output of this analysis will be a simple assessment criterion that can be applied by tank-car inspectors in the field.

A detailed analysis would include many variables such as tank size, wall thickness, tank materials, commodity properties, PRV set pressures and flow capacities, initial lading temperatures, initial lading fill levels, etc. It would not be reasonable to attempt to simulate all of these possibilities and therefore a baseline case will be examined for each system type (i.e. thermal protection and thermal insulation) and then a sensitivity analysis will be performed to show that these baselines reasonably cover all other possible cases.

The baseline for thermal protection will be a 112J340W tank filled with propane. For thermal insulation the baseline will be the 105A300W type tank.



### **3 Analysis of Thermal Protection Systems with Defects**

In this section we will only consider tanks that have thermal protection systems. The evaluation of defects will be based on how the defective systems respond to pool and torch fire environments.

#### **3.1 Thermal Protection Defect Assessment**

Thermal protection defect assessment will be based on how a tank responds to the two fire test cases – pool fire and torch fire. This determination will be done using computer models of tanks exposed to fire.

In this project we are analysing deficiencies in a critical safety component. If our analysis is wrong then the consequences may be severe. For this reason great care has been taken to ensure model predictions are reasonable.

It is important to understand that computer models are not perfect. They are not the real world and they usually cannot account for all possible factors. It is reasonable to select the best model available as a "standard" model to be used for comparison purposes. However, modelling uncertainties should be identified and quantified. It also makes good sense to include a reasonable factor of safety in any analysis that includes uncertainty.

This section will go into the details of the computer modelling process because it is critical that the computer models represent real-world behaviour of tanks. If an insulation defect can lead to premature tank failure in a fire we want to be able to show this using a suitable model.

#### **3.2 Tank Failure by Fire Exposure**

A tank will fail when the stress in the tank wall exceeds the tank strength. Tank wall strength is usually reduced by high wall temperatures in the vapour space of a tank exposed to fire.

The tank wall is put under stress by the tank internal pressure and by temperature gradients that introduce thermal stresses. These hoop stresses and thermal stresses may lead to vessel failure if they are severe enough and they have been applied long enough.

The tank internal pressure causes the well-known hoop and longitudinal stresses. The high wall temperature in the vapour space and the low temperature in the liquid space cause large thermal gradients, which cause the top of the tank to expand and bend the tank into a curve. This results in compressive loading on the tank top and tensile loading on the tank bottom.

These various stresses may lead to tank failure if the tank wall strength is reduced by high temperature.

### **3.2.1 Plastic Failure**

With plastic failure, the tank wall is usually heated to a point where the combined stress exceeds the yield strength of the material. Over time, plastic strain results in thinning of the wall locally and this results in elevated stress and more yielding. At some point the wall has thinned enough for a hole or tear to form in the wall, usually starting as a small hole near a local defect.

The tear will normally grow perpendicular to the hoop stress direction. If the stress is high enough and if the surrounding steel is weak enough the tear will run the full length of the tank and the tank will fail catastrophically, leading to a boiling liquid expanding vapour explosion (BLEVE). If the tear stops in stronger material before it runs the full length of the tank then the failure will be limited in size and the outcome will be a massive jet release.

These kinds of failure modes were observed by Birk et al (1997) in their fire tests of 400 litre ASME propane tanks.

### **3.2.2 Brittle Failure**

In this case the tank fails with little or no plastic deformation. The pressure and temperature loading of the vessel results in the local failure at a weld or plate defect. This type of failure can also happen if the tank is made from brittle steel. It should be noted that this type of failure is very difficult to predict because it can happen well below the normal ultimate strength of the material.

This type of failure should not happen in a well manufactured tank using ductile steel plate. This type of failure will not be considered in this report.

## **3.3 Tank Thermal Modelling with AFFTAC**

The US DOT and Transport Canada have accepted the computer code AFFTAC as the standard for thermal modelling of tanks in fires. The following section provides an overview and critique of this code and comments on its use in this study of insulation defects. Further details about AFFTAC can be found in Johnson (1998).

Important factors in fire exposure simulation include the following:

- fire heat flux (temperature and radiating properties)
- tank exposure (fraction of tank involved in fire)
- tank thermodynamic response

- PRV operating characteristics
- vapour space heat transfer and wall temperature prediction
- tank material properties and failure criteria

All of the above have uncertainty associated with them. Let us consider each in turn.

### 3.3.1 Pool Fire Heat Flux

In AFFTAC the pool fire is modelled as a black body radiating at 816° C. Fire convection is not accounted for separately. Based on pool fire data (see Rew et al (1997)) these are reasonable and credible assumptions for a kerosene fueled pool fire. However, other pool fire fuels (such as propane) would require higher fire temperatures.

In the CGSB standard the pool fire test specification requires a pool fire temperature of 871° C plus or minus 56° C. Therefore AFFTAC is using the lowest possible fire temperature to satisfy this specification. This approach has also been used in this study.

### 3.3.2 Torch Fire Heat Flux

For the torch fire it is usually assumed the heat transfer is by convection due to the jet impingement and by thermal radiation. In AFFTAC the torch is modelled considering radiation only.

The DOT standard torch must have a temperature of 1204° C plus or minus 56° C and must heat a 16 mm steel plate from ambient temperature to 427° C in 4 minutes (plus or minus 30 seconds). In the AFFTAC code this heat up time is achieved if the torch black body radiation is multiplied by a factor of 0.536 (assuming a tank surface emissivity of 0.8 which gives a total factor of  $0.536 \times 0.8 = 0.43$ ). This factor accounts for the effective emissivity and view factor for the torch used in the 1.2 m x 1.2 m plate tests.

This basic approach will also be used in this study with some modification (as described later).

### 3.3.3 Tank Exposure

The fraction of the tank exposed to the fire is an important factor because it affects how the tank pressurizes and how it empties through the PRV.

### 3.3.3.1 Pool Fire

In AFFTAC it is assumed the tank is 100% engulfed in fire. Real pool fires may not engulf a tank 100% depending on the fire size and the wind conditions. This suggests that the AFFTAC assumption is conservative with a factor of safety. However, the AFFTAC model may not be modelling a fully engulfing fire exactly.

The AFFTAC computer model has been developed to agree with the full scale fire test results (see Townsend et al (1974)) of protected and unprotected propane tanks (assuming a fire temperature of 816° C). It is very likely that these tanks were not fully engulfed in fire because of wind effects. This means that the vapour space wall temperatures in the fire test were not as high as they could have been with a full engulfing fire. This means then that the wall temperatures predicted in AFFTAC may not be conservative.

When an analysis has uncertainty, then a factor of safety should be applied. This will be discussed further later in this report.

### 3.3.3.2 Torch Fire

AFFTAC allows the user to specify the area of tank surface exposed to a torch. In the original DOT steel plate tests, the plate measured 1.2 m x 1.2 m. This exposure area has now been applied in the AFFTAC computer model as a default area for modelling a tank-car exposed to a torch fire.

If the AFFTAC model is being used to model the real world tank-car system then it should be modelling a credible torch environment. A 1.2 m by 1.2 m torch area (i.e. 1.5 m<sup>2</sup>) covers less than 1% of the surface of a 112 type tank-car and this in no way represents a credible torch fire accident. In a credible torch fire impingement case where one tank's PRV flare is impinging on another tank, the area of coverage could be more like 20-40% of the tank surface.

If it is assumed that the torch covers 1% of the tank then the tank will pressurize very, very slowly. In the CGSB standard a thermally protected tank must survive a torch for 30 minutes. If the tank does not pressurize in that 30 minutes it has a much better chance of surviving the test. Therefore assuming such a small torch area is not a conservative or credible assumption.

In this study, two torch cases will be considered. One where the torch area is 1.5 m<sup>2</sup> and one where the coverage is 30% of the tank surface.

### 3.3.4 Tank Thermodynamic Response

In AFFTAC it is assumed that the tank pressure is dictated by the liquid thermal properties. It is also assumed the liquid is isothermal, which means the heat added by the fire is distributed equally throughout the liquid. This assumption is incorrect based on numerous test results of tanks in fires (see Townsend et al (1974), Appleyard (1980), Birk (1983), Moodie et al (1988), Hadjisophocleous et al (1990), Birk and Cunningham (1997) ). In reality the liquid temperature is stratified in the tank during fire exposure (hot near the top and cooler near the bottom). This is due to free convection within the tank.

Fire tests of tank-cars have shown that the tank usually pressurizes much faster than predicted by uniform liquid thermal models. In real tanks, the liquid is not heated uniformly and this results in a hot layer of liquid which dictates the tank internal pressure. The full scale uninsulated tank tests of Townsend et al (1974) showed that the PRV opens after about 2 minutes and because of this early opening of the PRV the tank never went shell full of liquid. A uniform liquid thermal model will not predict this behaviour. With a uniform liquid thermal model the tank pressurizes about five times slower, which means the tank goes shell full of liquid and this causes the PRV to open.

This detail is very important to remember because when the tank goes shell full it means there is no vapour space and therefore there is no hot wall that can lead to tank failure. If a uniform liquid thermal model predicts a shell full condition in a tank exposed to fire then it is very likely the model will give poor predictions of wall temperature.

The uniform liquid temperature assumption in AFFTAC results in the following simulation errors:

- tank pressurization is too slow
- first opening of PRV is late
- late opening of PRV may result in tank going liquid full
- liquid full causes elimination of vapour space and erroneous wall temperature estimates

These errors mean that AFFTAC results may not be conservative. The AFFTAC assumption of isothermal liquid is not very important if the tank is well insulated and therefore the fire heat is added very slowly to the tank. However, if the tank thermal protection system is damaged then the AFFTAC assumptions may lead to significant errors.

For example,

- With torch exposure the AFFTAC model predicts very little pressure build-up in the tank due to the small torch exposure area. However, it is very likely that an actual tank system would experience pressure build-up due to liquid temperature stratification.



- In a pool fire test of an unprotected tank (see Townsend et al (1974)) filled 95% full of propane the PRV opened after about 2 minutes due to liquid temperature stratification. With AFFTAC this is not predicted. With AFFTAC the tank goes shell full of liquid before the PRV opens and this results in complete wall cooling. This was not observed in the field.

The conclusion here is that AFFTAC may not be conservative in the prediction of pressure build-up and vapour space wall temperatures. This is especially true for tanks with damaged or inadequate thermal protection systems. Once again this adds uncertainty to the analysis and therefore a factor of safety should be used.

### 3.3.5 Pressure Relief Valve Operation

The PRV is a critical part of this analysis. In AFFTAC the PRV opening and closing are modelled using four reference pressures.

- Start-to-discharge pressure ( $P_{std}$ ).
- PRV is fully open when the pressure is 103% of the std pressure ( $P_{fo}$ ).
- The valve is assumed to reclose fully at 82% of the std pressure ( $P_{fc}$ ).
- The closing stroke is assumed to start when the pressure has dropped to 88% of the std pressure ( $P_c$ ).

The blowdown of the valve is typically = pop pressure – reclose pressure. In this case AFFTAC is assuming a 21% blowdown. It should be noted that the maximum allowable blowdown is 20% (see Appendix K for PRV for CGSB requirements ) but PRVs may not have a blowdown this large.

In AFFTAC the open area of the PRV is assumed to be linearly interpolated between these reference pressures (for details see Johnson (1998)). It is not clear where these linear PRV operating characteristics have been obtained. It is very likely this method was used because it was numerically stable to do it this way in a computer model. In our opinion this is not a conservative way to model PRV action.

Real pop action relief valves do not generally fit the model described above. Typical relief valves have the following reference pressures:

- start-to-discharge pressure (simmer pressure, very little flow)
- pop pressure (pop to full open)
- reclose pressure (PRV closes to full close)
- reseal pressure (PRV)

With real valves the open area is not linearly related to these pressures. With a pop action PRV the valve is supposed to pop full open at some pressure and reclose fully when the pressure drops by some amount. A pop action PRV normally does not sit partially

open (although they do sometimes, but not with great consistency) unless the valves flow capacity is being approached (see Pierorazio and Birk (1998)). In pop action PRVs the valves cycle open and closed if the tank is generating vapour at a rate less than the PRV flow capacity. If the valves flow capacity is exceeded this results in the PRV being held full open. If the PRV is undersized for a given tank then the pressure will continue to rise even if the PRV is full open.

A cycling PRV exposes the tank to a pressure range between a high of the pop pressure and a low of the reclose pressure. This range may vary during a fire exposure event. The first few pops may be at higher pressures due to valve seat sticking (see Pierorazio and Birk (1998)). Later in the fire the pop and reclose pressures may decrease due to PRV spring softening due to high spring temperatures. However, this spring softening may not be significant until the tank is nearly empty.

In the simulation of a 112J340W tank (3 m diameter, 33000 gal capacity, 19 mm wall, surface emissivity = 0.9, 95% full, initial  $T = 20^{\circ}\text{C}$ ) with propane and 100% insulation defect (i.e. steel jacket but no insulation in gap), the peak PRV flow rate was estimated by AFFTAC to be about 17.9 kg/s (2360 lb/min) at about 24 minutes into the fire when the tank is 94% full of liquid. This is the full PRV flow capacity and by AFFTAC's PRV analysis requires the tank pressure to be 103% of the std pressure (i.e. 103% of 255 psi = 263 psi). However, at 60 minutes when the tank is only 30% full of liquid the PRV flow is 11.4 kg/s (1500 lb/min). This is well below the PRV flow capacity and therefore by AFFTAC's PRV model the tank pressure was only 222 psig. However, in reality the PRV probably would have been cycling between 210 and 263 psi. The reduced pressure assumed in AFFTAC results in lower calculated hoop stress and reduced chance of tank failure, which may be unrealistic and not conservative.

On the other hand a conservative analysis would assume that the PRV would cycle between its pop and reclose pressure when the full flow capacity of the PRV is not being used. For example, with a 112J340W tank the PRV std (start to discharge) pressure is 255 psig. At 100 min AFFTAC predicts tank pressure at 210 psi, while the tank burst pressure was 214 psi. This is a very close pass result. However, if the PRV was cycling between 103 and 82% of the std (i.e. 262 and 210 psi), then the tank would have failed during the high pressure part of the PRV cycle.

This is another example where the AFFTAC result may not be conservative. In this study it will be assumed that the tank is exposed to a hoop stress associated with a tank internal pressure = 103% of the PRV start-to-discharge pressure. In other words, the high side of the PRV cycle pressure will be used to calculate the hoop stress.

### 3.3.6 Prediction of Wall Temperatures

The wall temperatures in the liquid filled part of the vessel exposed to fire will be effectively cooled by the liquid. As a result the liquid wetted wall temperatures will be

close to the liquid temperature. The vapour space wall temperatures will get very hot because of the poor cooling effect of the vapour. A thermal model must be able to accurately predict vapour space wall temperatures, to predict tank failure.

The vapour space wall temperature is affected by the vapour, and the liquid. The hot vapour space wall convects heat to the vapour and radiates heat to the vapour, the liquid surface and to itself (because the wall is concave). The liquid surface will be relatively cool (its temperature is limited by the PRV set pressure). Therefore, the vapour space wall will be cooler for high fill levels than for low fill levels. Also, heat will be conducted from the hot vapour space wall to the wall cooled by liquid. This also results in lower vapour space wall temperatures when the fill level is high.

When the PRV opens there will be swelling of the liquid due to bubble formation in the liquid. This causes the liquid level to rise and cause the vapour space wall area to shrink. Of course if the tank goes liquid full then there is no vapour space wall and all of the tank wall is cooled. As long as the tank wall is cool and the pressure in the tank is near the PRV set pressure the tank is not expected to fail.

The following assumptions are used to model the vapour space heat transfer in AFFTAC:

- vapour space cooling is dominated by thermal radiation to the liquid surface
- absorption of radiation by the vapour is ignored
- the view factor from the vapour space wall to the liquid surface is equal to the ratio of (liquid surface area/ vapour space wall area)

With these assumptions the vapour space wall temperature will continue to increase as the liquid level drops. When the liquid is emptied from the tank the vapour space wall temperature will increase more rapidly. With this assumption it is very likely that a tank will fail soon after it is empty if it does not fail earlier.

In other words, with AFFTAC a critical time for the tank is the time to empty. With AFFTAC, a tank deficient of insulation will probably fail soon after it is empty if it does not fail earlier. This will be demonstrated later in this report.

### 3.3.7 Effect of Liquid Fill

If a tank is exposed to fire then heat will be added to the tank and lading. If a tank starts off 90% full of liquid and if heat is added to the liquid uniformly (as assumed in AFFTAC) then the tank will go liquid full before the PRV opens and vents material. This is a possible scenario for a well insulated tank where heat is added slowly. However, it is known from fire tests of uninsulated tanks (see Townsend et al (1974)) that the heat is not added uniformly to the liquid and therefore the PRV usually opens before the tank is shell full of liquid.



In AFFTAC the temperature increase will cause the liquid lading to expand and at some point the vessel will become liquid full. Once the tank is liquid full, AFFTAC calculates the necessary PRV liquid flow to allow for liquid thermal expansion.

Table 3-1 illustrates how propane expands with increasing temperature.

**Table 3-1: Propane Liquid Expansion with Temperature**

Propane T (°C)	Expansion Factor e	1/e
20	1	1
25	1.016	0.984
30	1.032	0.969
35	1.05	0.952
40	1.07	0.935
43	1.082	0.924
45	1.091	0.917
50	1.114	0.898
55	1.14	0.877
60	1.169	0.855

If a typical propane PRV is set at around 2 Mpa (290 psi) then this equates to a propane temperature of about 60 °C. In this case any tank starting at 20 °C that is filled more than 85% is likely to go liquid full before the PRV opens (this ignores liquid temperature stratification which can open the PRV earlier).

If the tank goes liquid full the entire tank wall will be cooled and as long as the PRV limits the pressure, the tank will not fail due to high wall temperatures. For high wall temperatures to be established the liquid level must drop to expose vapour space wall. The erroneous calculation of shell full condition leads to incorrect vapour space wall cooling. This feature of AFFTAC may result in the erroneous calculation of low vapour space wall temperatures. Once again this is an example of where AFFTAC is not conservative.

In a typical scenario where a tank starts 95% full the tank will take several minutes to reach a liquid full state. In the AFFTAC model, if the tank does not fail before the tank goes liquid full then the rising liquid will cool the wall and save the tank. Failure of the tank must now wait until the liquid begins to drop so that a vapour space can be reformed.

Consider the following scenarios:

- i) tank engulfed or partially engulfed in pool fire  
-- rapid vapour space wall heating

- rapid liquid heating
  - tank goes liquid full before critical wall temperature achieved
  - probable failure after liquid level drops from liquid full condition
- ii) tank exposed to local torch fire
- very rapid vapour space wall heating
  - lower liquid heating
  - tank may fail before it goes liquid full

The time to failure in these different cases depends on how quickly the vapour space wall is heated and how quickly the total liquid is heated. The wall heating causes it to weaken. The overall heating causes the liquid level to rise to cool the wall. It is a race between the wall heating and the rising liquid to determine whether the tank will fail early or later in the AFFTAC model.

The above process is not so true for tanks that are only filled to say 80%. These tanks will not go liquid full before the PRV opens.

### 3.3.8 Tank Material Properties and Failure Criteria

The tank material properties used in AFFTAC use the minimum allowable tensile strength based on the steel type. Therefore, there is some factor of safety here because the steel properties are usually better than the minimum allowed. However, the failure model used in AFFTAC is very simplistic and is not conservative.

The AFFTAC failure model assumes tank failure when the tank hoop stress exceeds the material tensile strength at the elevated wall temperature. However, at elevated temperatures steels can creep resulting in creep ruptures at stress levels well below the material tensile strength. Stress rupture properties of steels at elevated temperatures have some scatter and therefore there is some uncertainty here. As a result, AFFTAC failure estimates may not be conservative.

### 3.3.9 Tank Failure Analysis Methods

In this study the tank failure analysis assumes a ductile type failure. Ductile tank failure can be predicted in a number of ways. The following list includes methods increasing in complexity.

- i) when hoop stress exceeds ultimate tensile strength based on peak wall temperature (or when tank pressure exceeds burst pressure based on peak wall temperature).
- ii) when hoop stress exceeds yield stress based on peak wall temperature. The yielding accumulates as a function of stress, wall temperature and time until tank failure is indicated.

iii) detailed shell temperature and stress is calculated using finite element methods and plastic deformation : calculated as a function of time.

The method described in i) above is the simplest method to implement because it requires the least amount of data input. The data needed is simply steel ultimate strength vs temperature. The AFFTAC code uses the method described in i) above. This method will be used in this study as the baseline method to predict failure. This method is simple but it may not be a conservative approach. With this method, if the tank stress does not exceed the ultimate stress then the tank will not fail. However, in practice it is known that steel failure can happen with stress below the ultimate tensile strength of the material if the load is applied long enough to allow accumulation of creep.

In the second method, if the stress exceeds the yield but is less than the ultimate the tank can still fail if the stress is applied for a long enough period of time. With this method more property data is needed. The data must include time to tensile failure as a function of steel temperature and stress. This model is more difficult to implement because of the added data requirements. Very limited data is available for the steels of interest in this study.

The third method noted above is the most complex and most difficult to perform. It requires lengthy computer simulations. In this study we are interested in hot spots resulting from insulation defects. These hot spots will not be subjected to the same stress as the rest of the tank and therefore this method may be required to give the most accurate picture of the effects of insulation defects.

### 3.3.10 Tank Pass or Fail

For the CGSB standard a thermally protected tank must not release material (other than through the PRV) for 100 minutes when exposed to a 816° C pool fire. In this study the simulation results will be shown for both time-to-empty and time to failure.

A very valid question is raised here – will a tank fail after it is liquid empty? The AFFTAC model contains heat transfer assumptions that may result in tank failure shortly after it is liquid empty.

The full scale fire test of an insulated tank (see Townsend et al (1974)) resulted in tank failure when the tank was 2% full. However, other tests of tanks (see Appleyard (1980), Birk et al (1997)) have shown that once the tank is empty of liquid the test is basically over and the tank will not fail. This is usually because once the liquid is gone the tank usually loses pressure through the PRV. The high temperatures of the vapour only environment usually result in overheating of the PRV spring which causes spring relaxation. This spring weakening causes the blowdown of the tank to atmospheric pressure. Once the pressure is gone the tank cannot fail.

Is it safe to assume the tank will not fail after it is empty? Probably not. It is conservative to assume that the wall will continue to get hotter after the tank empties and this may result in failure. Therefore it probably is not safe to say that a tank passes the test if it empties before the 100 min time limit for pool fires.

### **3.4 Thermal Modelling of Defects with TMID Code**

A program has been developed to model a tank with part of the tank surface covered by insulation defects. This program has been given the name TMID for Tank Model with Insulation Defects. The TMID thermal model was used to simulate the effects of torch or pool fire impingement on a rail tank-car equipped with defective thermal protection. A complete listing of TMID is in Appendix C.

The thermal model developed for this study has used assumptions similar to those used in the US FRA computer code AFFTAC (Ver 3.0, Nov 1998). This was done as directed by Transport Canada. It has already been suggested that AFFTAC has some modelling deficiencies that can affect the results of this study.

#### **3.4.1 TMID Assumptions**

TMID is based on assumptions similar to the AFFTAC code but with the necessary features to model insulation defects that cover only parts of the tank. These include:

- thermal radiation in gap between steel jacket and wall
- vapour space radiation with hot spot (defect) cool zone (insulated wall) and liquid surface
- effect of liquid level on defect temperatures (i.e. as liquid level drops it exposes defective area to vapour space, etc).
- defect is modelled as a strip that runs the entire length of the tank on one side (strip defined by angle from tank top to defect top and bottom)

In TMID it is assumed that the defect temperature and stress are uniform. In other words, two- and three-dimensional effects such as circumferential or axial heat conduction or thermal expansion are ignored. These effects will be discussed later in this report when local effects are considered.

The maximum normal stress in the defect is assumed to equal the tank hoop stress. The tank material strength in the defect is assumed to equal the strength based on the material properties (i.e. ultimate tensile strength) for the defect temperature.

The code is not fully validated (because data is not available for validation). The code does appear to be producing reasonable results. Where possible, simulation results have been compared with AFFTAC results with reasonable agreement (see Appendix D).

The code is not exactly the same as AFFTAC. The most significant difference is associated with how the PRV is modelled. In AFFTAC the PRV is modelled in the following way:

- PRV opens at 103% of PRV start-to-discharge pressure (std)
- PRV recloses at 82% of std
- PRV flow capacity based on PRV rating (SCFM air), rating pressure (usually 110% of start-to-discharge pressure) and assumed flow coefficients (0.8 for vapour, 0.6 for liquid).
- PRV flow is linearly related to opening and closing pressures

In a thermally protected tank with partial insulation defect, the PRV will most likely cycle open and closed between the PRV open pressure and close pressure. This assumes the PRV has been sized properly (as per AAR PRV sizing formulas) and it therefore provides more than enough flow capacity for a thermally protected tank. If a PRV std pressure of 280 psig is used (i.e. for 112J340W tank) then this means the tank pressure cycles between about 1.6 and 2.0 MPa (230 and 288 psig). In TMID it is assumed that the tank will fail at the high point of this cycle, therefore in TMID it is assumed the tank pressure is held at 103% of the std pressure and the PRV mass flow is calculated based on energy considerations to maintain this pressure in the tank.

In TMID the tank is modelled as a long cylinder (i.e. it is a two-dimensional model), filled with liquid and its vapour. The model includes the following basic elements.

The following sections briefly identify differences between TMID and AFFTAC.

### 3.4.2 Fire Heat Transfer

The fire heat transfer is the driver in this analysis. Two different fire types are considered, a pool fire and a torch fire.

#### 3.4.2.1 Pool Fire

In TMID it will be assumed that the fire radiates as a black body at 816° C. However the tank outer surface emissivity will be set at 0.9 (AFFTAC uses 0.8), which is considered to be more valid for tank-car finishes (see Appendix I).

#### 3.4.2.2 Torch Fire

For the torch fire the temperature will be 1204° C as in AFFTAC. In AFFTAC a factor of 0.536 is applied like an emissivity to the torch radiation to satisfy the temperature vs time requirement. However this factor is then multiplied by the tank emissivity in AFFTAC (0.8) to get the final heat input ( $0.536 \times 0.8 = 0.43$ ).

In TMID the factor is 0.45 and the surface emissivity is 0.9 ( $0.9 \times 0.45 = 0.41$ ).



### 3.4.3 Thermodynamic Model

The tank interior volume is divided into two basic regions, the vapour space and the liquid space. The thermodynamic model is needed to predict how these regions change as heat is added to the tank from the fire.

In the AFFTAC model these two regions are assumed to be of uniform temperature and in saturated thermodynamic equilibrium. Heat enters the liquid space through the liquid wetted wall by convection, and at the liquid surface by radiation from the vapour space wall. Heat enters the vapour by convection from the vapour space wall.

This same model is used in TMID. This model ignores liquid temperature stratification, which can have an important impact on the predicted results.

A more accurate thermal model would consider the liquid temperature stratification. Birk (1983) used a two-node thermal model (i.e. saturated vapour space with saturated liquid boundary and sub-cooled liquid core). With this model it was possible to predict the correct time for first PRV action and the correct liquid level. With the correct liquid level it is possible to accurately predict the wall temperatures in the vapour space.

Since AFFTAC is the standard computer code used by the FRA and Transport Canada, its basic methods will be used in this study. Therefore a single node thermal model has been used in this study. Where possible the report will point out where results may not be accurate. In addition a factor of safety will be applied to offset the simulation uncertainties.

### 3.4.4 Wall Heat Transfer Models

The wall, thermal barrier and jacket heat transfer is by pure conduction. If no insulation is present in the gap between the tank and jacket then the heat transfer in the gap is by thermal radiation and convection. For defects it has been assumed that air is in the gap and the defect is closed so that the air is stagnant (i.e. convection is ignored).

The time varying wall temperatures are calculated using an explicit finite difference technique. The following wall temperatures are calculated for this study.

- vapour space wall under insulation defect
- vapour space wall in insulated area
- liquid space wall under insulation defect
- liquid space wall in insulated area



Temperature gradients through the steel are ignored; circumferential conduction of heat around the tank wall is also ignored. These assumptions are consistent with the AFFTAC code and are conservative.

### 3.4.5 Thermal Radiation in Vapour Space

The interior heat transfer is by thermal radiation and convection. The tank vapour space interior surfaces are divided into the following regions:

- 1g wall area of defect in vapour space
- 1f wall area of defect in liquid space
- 2g protected/insulated wall area in vapour space
- 2f protected/insulated wall area in liquid space
- 3 liquid surface

The vapour space wall areas will be hot due to the poor cooling effects of the vapour. The defect area in the vapour space will be hotter than the insulated part of the vapour space wall. The liquid wetted wall will be cool due to the strong cooling effects of the liquid.

In the vapour space heat is lost from the wall by thermal radiation and convection. When the wall gets hot thermal radiation will dominate. The wall areas will radiate to the other visible wall areas and liquid surface. The vapour will also absorb thermal radiation.

Absorption of radiation by the vapour has been ignored in the AFFTAC model. This assumption is probably conservative. It should be noted that the vapour will in fact absorb thermal radiation significantly. This absorption of radiation by the vapour will reduce the cooling influence of the liquid surface. In other words, if vapour absorption is included then the wall temperature in the vapour space will not rise as rapidly with dropping liquid level.

The radiation view factors in the vapour space were calculated using Hottel's crossed strings method (see Hottel and Sarofim (1967)). Three zones are considered - 1g, 2g and 3. This method applies for two-dimensional systems (i.e. very long cylinders) and therefore ignores the effects of the tank ends. It also means the model is limited to defects that run the entire length of the tank.

The tank inside surface is assumed to have an emissivity of 0.9 (AFFTAC assumes 0.8). The liquid surface is assumed to have an emissivity of 0.9 (as per AFFTAC).

### 3.4.6 Convection in Vapour Space

For convection, AFFTAC assumes the following:

i) when tank is more than 0.4 full but less than 0.9 full, and the PRV is venting

$$h = 0.05 \text{ Btu/hr ft}^2\text{°F} = 0.284 \text{ W/m}^2 \text{ K}$$

A larger value is used when the PRV is venting more than 1500 lb/min. It is not clear what the code uses in this case. In any case, the above convective coefficient is so small it can be ignored compared to the thermal radiation.

ii) when tank is empty of liquid AFFTAC assumes

$$h = 1.0 \text{ Btu/hr ft}^2\text{°F} = 5.7 \text{ W/m}^2 \text{ K}$$

It is not clear why this is used. Why should there be a 20 x increase in  $h$  suddenly when the liquid is gone? In fact, the heat transfer to the vapour will be primarily by thermal radiation, but this has been ignored in the AFFTAC model.

In the present model, convection has been ignored in the vapour space (the AFFTAC assumed  $h$  is negligibly small). The simulation ends when the tank is empty. The AFFTAC assumptions normally lead to tank failure shortly after the tank is empty (i.e. if it does not fail earlier).

### 3.4.7 Convection in Liquid Space

Thermal radiation is ignored for the liquid wetted wall. The heat transfer is by liquid convection or boiling. In the liquid space the wall is strongly cooled by convection and boiling. In this case  $h$  is assumed to be  $1000 \text{ W/m}^2 \text{ K}$ . This forces the tank wall temperature to remain close to the liquid temperature which it does based on observations from various fire tests of tank-cars.

### 3.4.8 Properties of Thermal Insulation

The thermal properties of the high temperature insulation material is an important factor in this analysis. Fiberfrax or Kaowool ceramic blanket has the following thermal conductivity ( $k$  with units  $\text{W/mK}$ ) as a function of temperature (see data sheets in Appendix F).

Table 3-2: Summary of Thermal Data vs Temperature for Fibrefrax Insulation (72 kg/m<sup>3</sup> density)

Temperature (°C)	Thermal Conductivity (W/mK)	Thermal Conductivity (Btu in/hr/ft <sup>2</sup> /F)
20	0.03	0.2
200	0.06	0.4
600	0.17	1.2
700	0.23	1.6

If we assume a 13 mm layer of blanket (as used in thermal protection system) at 600° C we expect a conductance of  $0.17/0.013 = 13.1 \text{ W/m}^2\text{K}$ . At 650° C we expect  $0.202 \text{ W/mK}$  conductivity and  $15.5 \text{ W/m}^2\text{K}$  conductance for 13 mm thickness. If this 13 mm layer is compressed to half of this (6.5 mm) the insulation density increases to about  $140 \text{ W/m}^2\text{K}$  and this reduces the k to about  $0.13 \text{ W/mK}$  ( $0.85 \text{ Btu in/ft hr deg F}$ ) at around 600° C. This translates to a conductance of  $20 \text{ W/m}^2 \text{ K}$  ( $3.4 \text{ Btu/hr ft}^2 \text{ F}$ ).

In an earlier report, Johnson (1995) stated that a thermal protection system that satisfies the pool fire requirement (CFR 179.105-4) would have at most a conductance of  $22.7 \text{ W/m}^2 \text{ K}$  ( $4.0 \text{ Btu/hr ft}^2 \text{ F}$ ). In this report it will be assumed that the thermal protection system has a thermal conductance of  $22.7 \text{ W/m}^2 \text{ K}$  ( $4.0 \text{ Btu/hr ft}^2 \text{ F}$ ) except where there are defects. A sensitivity analysis will also be performed to show the effects of ideal insulation properties as described above.

### 3.4.9 Ultimate Tensile Strength

In the AFFTAC model, the following equation is used to account for the high temperature degradation of TC-128. AFFTAC assumes that all low to moderate alloy carbon steels have similar high temperature properties.

for  $T_{\text{wall}} < 1260 \text{ R}$

$$\text{FCTR} = 1.0 - 0.54(\text{TTNV} - 0.46)^4$$

for  $T_{\text{wall}} > 1260 \text{ R}$

$$\text{FCTR} = 1.74 - 1.17(\text{TTNV} - 0.46)$$

where

TTNV = vapour space wall temperature (° R/1000)

FCTR = ratio of ultimate stress at T to ultimate stress at ambient temperature

The ultimate stress of the material can then be determined by multiplying FCTR times the material ultimate strength at ambient temperature. The tank burst strength is determined by multiplying the FCTR times the ambient temperature burst strength.

TC 128 pressure vessel steel has a minimum tensile strength of 560 MPa (81000 psi) at ambient temperature. This ultimate strength has been used in this study.

#### 3.4.10 Stress, Temperature and Time to Failure Data

Creep rupture data for TC 128 was reported by Anderson and Norris (1974) This data is needed for predicting the time to failure if the tank stress is below the ultimate tensile strength, but it is high enough to cause plastic deformation over time. This data will be shown later when failure prediction uncertainty is discussed.

#### 3.4.11 Factor of Safety (FOS)

As stated earlier it seems prudent to include a factor of safety (FOS) to account for some uncertainties in the analysis of a thermally protected tank with insulation defects exposed to a pool or torch fire.

For a pool fire simulation, one way to define FOS is as follows:

$$FOS_{bp} = (\text{tank burst pressure at 100 minutes})/(\text{tank pressure at 100 minutes})$$

The subscript bp is used to indicate that the FOS is based on burst pressure. Another way to define FOS is based on time to failure.

$$FOS_t = (\text{time to predicted failure})/100 \text{ min}$$

It is somewhat arbitrary which FOS we use. In this report we will use  $FOS_{bp}$  and from this point on, it will be designated only as FOS.

The reader is cautioned on how to interpret FOS. An  $FOS = 2$  means that the tank is two times as strong as it needs to be at the 100 minute time. However, at high wall temperatures this  $FOS = 2$  may only provide 5 or 10 minutes of extra time before failure.

In AFFTAC the tank fails when  $FOS = 1.0$ . Therefore, we want the FOS to be greater than 1.0 to account for analysis uncertainties. The question is how much greater than 1.0 is prudent? We should set a FOS that accounts for the uncertainty in the following:

- fire exposure and temperature
- PRV behavior (open and closing pressures)
- tank fill level effects (shell full, etc.)
- tank material properties and failure criteria

Let us recall the DOT insulation test standard where a sample of insulation was tested by fire exposure on a 1.2 m x 1.2 m steel plate. The limit of acceptance for insulation materials was as follows:

pool fire test	test plate $T < 427^{\circ}\text{C}$ for 100 minutes
torch fire test	test plate $T < 427^{\circ}\text{C}$ for 30 minutes

If we compare the temperature limit of  $427^{\circ}\text{C}$  to the current AFFTAC simulation standard of tank failure we can derive an FOS from the test standard. The current simulation standard (AFFTAC) will predict tank failure (for 112 type car, 95% full of propane, just steel jacket) from pool fire exposure, if the tank wall reaches about  $640^{\circ}\text{C}$  –  $700^{\circ}\text{C}$  (depending on wall thickness and PRV pressure) within 100 minutes. At  $640^{\circ}\text{C}$  TC 128 steel has a strength of about 200 Mpa. At  $427^{\circ}\text{C}$  TC 128 has a strength of about 450 Mpa. In other words, the FOS from the plate tests was  $450/200 = 2.3$ .

If we want the same FOS to apply to a tank with insulation defects, we must set the allowable wall temperature to  $427^{\circ}\text{C}$  for the pool and torch fire simulations. Unfortunately if we do this all insulation defects will fail the simulation tests. This is not an unreasonable outcome because there is no insulation in the defective areas!

Let us try to select some intermediate FOS between 2.3 and 1.0. Let us consider the following uncertainties.

#### 3.4.11.1 *Uncertainty in Fire Temperature*

The current pool fire simulation condition assumes a fire temperature of  $816^{\circ}\text{C}$ . However the actual plate test specification requires  $871^{\circ}\text{C}$  plus or minus  $55^{\circ}\text{C}$ . A fire at  $871^{\circ}\text{C}$  produces 1.22 times as much radiant heat flux as a fire at  $816^{\circ}\text{C}$ . This increased heat flux causes higher wall temperatures and a reduced tank burst pressure.

The plate test simulates a kerosene or JP pool fire as used in pool fire tests of propane tanks (see for example Townsend et al (1974)). However, in the real-world scenario the pool fire fuel could be other fuels such as propane, pentane, etc. These fuels can burn hotter than kerosene. Actual flame temperatures depend on many factors including the fire scale, fuel, and wind conditions. Table 3-3 shows how different pool fire fuels have different effective radiating temperatures.

As shown above pool fire temperatures can be much hotter than  $816^{\circ}\text{C}$ . Nakos and Keltner (1989) reported very detailed heat transfer measurements in a JP4 pool fire (9m x 18m rectangle). They recorded average total heat fluxes of between 120 and 128  $\text{kW/m}^2$ , which is in good agreement with the above table. Therefore, it is clear that the AFFTAC assumption of  $816^{\circ}\text{C}$  is not conservative for a large JP4 pool fire.



**Table 3-3: Maximum Pool Fire Radiating Temperatures (data from Rew et al (1997))**

	<b>Maximum Pool Fire Heat Flux to Cool Surface</b>	<b>Maximum Effective Radiating Temperature (assuming flame emissivity of 1.0 and flux is 100% radiation)</b>
<b>AFFTAC</b>	<b>79 kW/m<sup>2</sup></b>	<b>816 °C</b>
<b>plate test</b>	<b>97</b>	<b>871</b>
butane	225	1140
diesel oil	130	960
gasoline	130	960
JP 4	130	960
kerosene	130	960
propane	250	1180
octane	200	1100
LNG	265	1200
pentane	200	1100
toluene	130	960

Let us for now consider the case of a 871° C fire (which is still not conservative).  
Let us consider the following example:

112J340W tank fill 90% with propane  
17.5 mm wall with TC 128  
insulation defect from 0-90° around tank side (25% defect)  
initial temperature 16 °C  
PRV limited tank pressure P = 2 MPa

**Table 3-4: TMID Simulation Showing Effect of Fire Temperature**

<b>Conditions at 100 minutes</b>	<b>Fire T = 816° C</b>	<b>Fire T = 871° C</b>
Wall Temperature (°C)	597	649
Tank Pressure (MPa)	2	2
Burst Pressure (MPa)	2.9	2.2
FOS	1.45	1.1
Fill	37%	25%

It can be shown that a 22% increase in heat flux will result in a 9% increase in wall temperature (under jacket) and this leads to a 25% decrease in burst pressure. Therefore a

factor of safety of 1.25 is suggested here to account for possible variations in fire conditions.

#### 3.4.11.2 *Uncertainty in PRV Behavior*

Another example of uncertainty is the PRV open and close conditions. In AFFTAC it is assumed that the PRV pops open at 103% of the start-to-discharge (STD) pressure and it closes at 0.82 of the STD. In TMID it is assumed the tank pressure is maintained at 103% of STD pressure and the PRV mass flow is whatever is needed to satisfy the energy balance on the tank.

For a 112J340W tank with a nominal 5.9 MPag (850 psig) burst pressure the maximum STD pressure =  $0.33 \times 5.9 = 1.93$  MPag (280.5 psig). There is a 3% tolerance on this pressure and therefore the pressure could go up to 1.99 MPag (289 psig). The flow rating pressure is 110% of the STD pressure or 2.19 MPag (318 psig).

The main question is when will the PRV open fully or pop to relieve pressure? The STD pressure is when flow begins in the PRV. This could be when the PRV begins to leak. Full flow is not obtained until the PRV pops open. A full pop must happen at or before the flow rating pressure which is 110% of the STD pressure, or it may happen at the STD pressure. Therefore, there is an uncertainty of 10% here.

Smaller scale PRVs (1-2 inch) have been shown to have variability in the pop pressure (see Pierorazio and Birk (1998)). No data exists that can be used to describe the variability of tank-car scale PRVs. Therefore an FOS of 1.1 will be applied to the tank burst pressure to account for PRV uncertainty.

#### 3.4.11.3 *Tank Initial Fill*

Tank initial fill uncertainty is harder to quantify because it has several effects. Lower fills mean higher wall temperatures and faster emptying of the tank. Low fills also affect whether the tank will go shell full during the fire exposure event. In this study we were told to assume the tank was filled to its maximum allowable level for propane (i.e. when tank heated from 16 C to 43 C tank goes 99% full). For this we have assumed 90% initial fill. Let us now consider the case with a 80% fill.

Let us again consider the following example:

112J340W with propane  
17 .5 mm wall with TC 128  
insulation defect from 0-90° around tank side  
initial temperature 16 °C  
PRV limited tank pressure  $P = 2$  MPa

**Table 3-5: Simulation Showing Effect of Initial Fill**

Conditions	Initial fill 90%	80%
Wall Temperature (°C) at 100 min	597	603
Tank Pressure (MPa) at 100 min	2	2
Burst Pressure (MPa) at 100 min	2.9	2.8
Fill at 100 min	37%	30%
FOS at 100 min	1.45	1.40
Time for wall to T = 427 °C	16 min	16 min
Time to liquid full	29 min	not filled
Time for wall to recover to 427 °C	54 min	na
Fail time with FOS = 1.6	75 min	56 min

This uncertainty in fill can affect the overall calculation results significantly because it affects whether the tank will go liquid full or not. The uncertainty here is that AFFTAC predicts a shell full condition when in the real world, a shell full condition may not occur. As can be seen from the table a small change in initial fill can have a dramatic effect on how the vapour space wall heats up.

However, the fill level change shown above does not appear to change the overall outcome of the simulation at the 100 minute mark. Therefore, no factor will be applied here to account for fill level uncertainty.

#### 3.4.11.4 *Uncertainty in Tank Material Properties*

In AFFTAC the tank is assumed to fail immediately when the tank pressure equals 100% of the tank burst pressure. However, if the tank pressure were say 99% of the burst pressure then, in reality, the tank would probably still fail after some time is accumulated. This is because of the stress-temperature-time rupture characteristics of steel. This is not accounted for in AFFTAC. Therefore a FOS should be applied to the basic failure criteria to account for this uncertainty.

Anderson and Norris (1974) show stress-temperature-time to rupture data for TC 128 steel samples. This data is shown in Table 3-6.

**Table 3-6: Stress-Temperature-Time to Rupture Data for TC 128 Steel (from Anderson and Norris (1974))**

Sample Temperature (°C)	Stress in Sample (000's of psi)	% of Ultimate Strength at Temperature	Time to Failure (min)
482	77	100	0 tensile test
482	65	84	16
482	62	81	244
566	60	100	0 tensile test
566	49	82	52
566	42	70	138
649	49	100	0 tensile test
649	32	65	6
649	30	61	36
649	20	41	115

The above data clearly shows how stress and temperature affect the time to failure of a test sample. The data shows that it does not take tensile stress at 100% of ultimate strength to cause failure. For example, at 649 °C steel temperature it took only 6 minutes to fail a sample even though it was only stressed to 65% of its ultimate strength. However, at 482 °C it took 244 minutes to fail a sample that was stressed to 81% of the sample ultimate strength. Now we must try to select an uncertainty factor to account for this behavior.

With TC 128 at 649 °C the samples failed even at low stress levels (65% of ultimate). We should never let the tank steel achieve such temperatures. At 566 °C a stress at 82% of the ultimate resulted in failure after 52 minutes. This time fits well within the pool fire 100 minute requirement. Therefore, let us use this condition to draw the line. We will therefore assume that if the stress reaches 80% of the material ultimate strength the tank will fail within minutes. Based on the above it is suggested that a factor of  $100/80 = 1.25$  be applied to the tank burst pressure to account for stress-temperature-time to failure uncertainty.

Now, let us add up all these uncertainties:

- i) fire heat flux uncertainty factor = 1.25

- ii) tank pressure uncertainty factor = 1.1
- iii) Tank fill uncertainty factor = 1.0
- iv) failure criteria uncertainty 1.25

Overall uncertainty in the burst pressure then becomes  $0.25 + 0.1 + 0.25 = 0.60$ , which gives a FOS = 1.6.

Let us now proceed with this as a FOS. (i.e. FOS = 1.6). If we do this then we will find that all defects will pass the torch test (as they already do with AFFTAC), but large defects will fail the pool fire test.

### 3.5 Validation

This section shows a brief comparison between the AFFTAC and TMID computer models. The comparison is based on the case of an unprotected tank car exposed to an engulfing fire. This simulation is used as a benchmark because good data is available for this case (see Townsend et al (1974)). In this case the tank failed at about 24 minutes in the engulfing fire.

The following inputs were used:

no thermal protection  
 propane  
 TC 128 tank steel  
 tank diameter            3 m  
 tank length              18 m  
 initial fill                95%  
 initial temperature      16 °C  
 fire temperature        816 °C  
 fire emissivity          1.0  
 100% engulfment

The PRV limited tank operating pressure was set at 2.5 MPa for TMID. In AFFTAC, the PRV std was 1.9 MPa and the PRV flow capacity was 12.3 m<sup>3</sup>/s (26000 SCFM). Surface emissivity was 0.8 for AFFTAC and 0.9 for TMID.

The results are shown in Figure 3-1 to Figure 3-10. Five plots are shown:

1. P and P burst vs time
2. vapour space and liquid space wall T vs Time
3. volume fill vs time
4. PRV mass flow vs time
5. FOS vs time



The following can be seen in the figures.

- Both models predict shell full at about 4 minutes.
- There is a slight difference between the models for the time when the fill drops below 100% -- time is 10 minutes for AFFTAC and 13 minutes for TMID. This is probably due to differences in PRV action.
- Both models predict tank failure at about 24-25 minutes.
- Both models predicted a fill of about 45% at tank failure.
- Both models predict vapour space wall temperatures of 650 °C at about 24 minutes.
- PRV mass flow rates are of similar magnitude but the shape of the curve over time is quite different. This is due to the different PRV assumptions between AFFTAC and TMID. Note however that both have nominal flow rates of between 20 – 35 kg/s when the PRV is in full action.

The plot of FOS vs time deserves comment. The two models have very similar FOS curves. Both models predict an FOS of 2.0 at about 20 minutes into the simulation. This means that at the 20 minute mark the tanks were two times as strong as needed to survive the pressure. However, only 4-5 minutes later the FOS has dropped to 1.0 for indicated failure. In other words this FOS = 2 only provided 4-5 minutes of time before failure. This clearly shows that we must be very careful how we determine tank failure times. In this report, an FOS of 1.6 was suggested as reasonable. The TMID and AFFTAC codes predict FOS = 1.6 for an unprotected tank at about 21-22 minutes. This FOS of 1.6 only provided a 2-3 minute cushion. Clearly an FOS of 1.6 is not excessive.

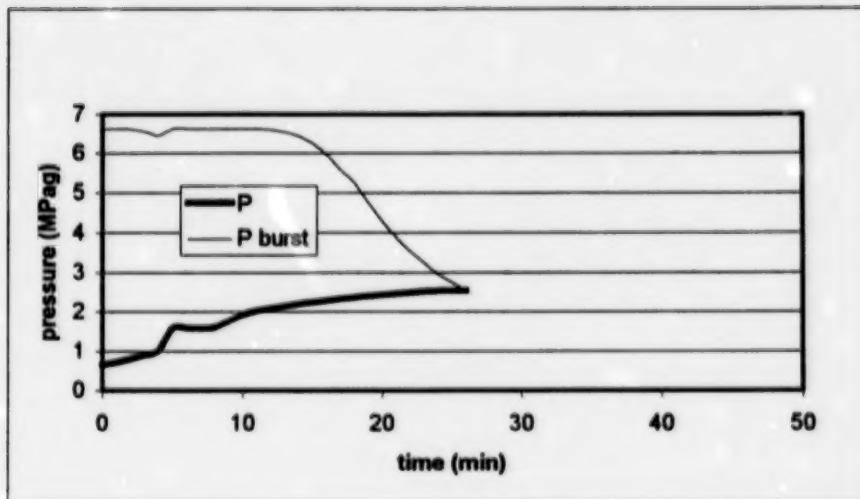


Figure 3-1: Predicted Tank Pressure vs Time (AFFTAC)

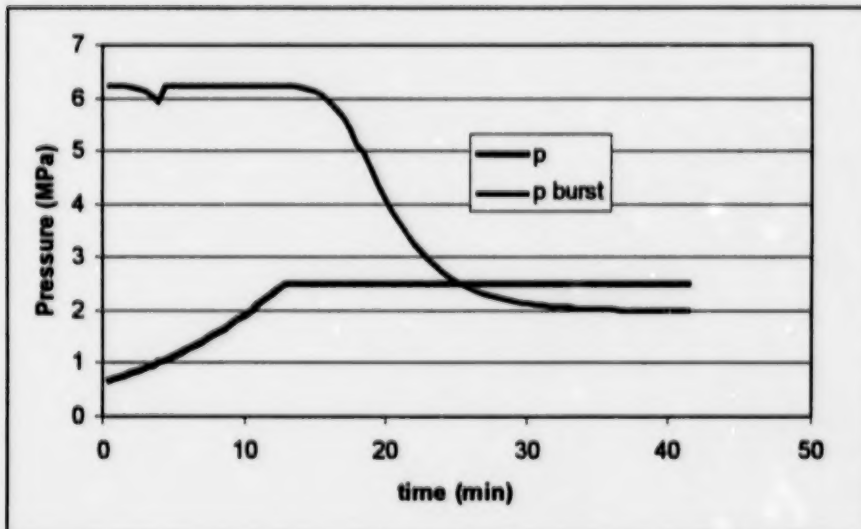


Figure 3-2: Predicted Tank Pressure vs Time (TMID)

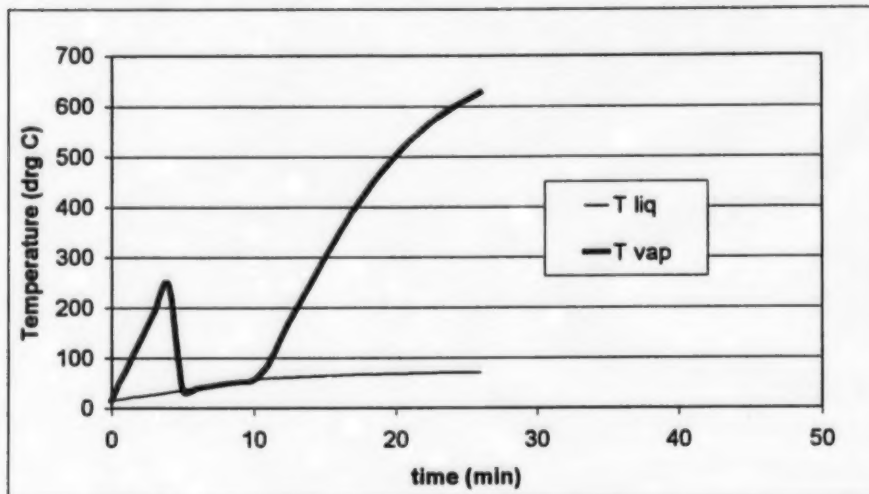


Figure 3-3: Predicted Wall Temperature vs Time (AFFTAC)

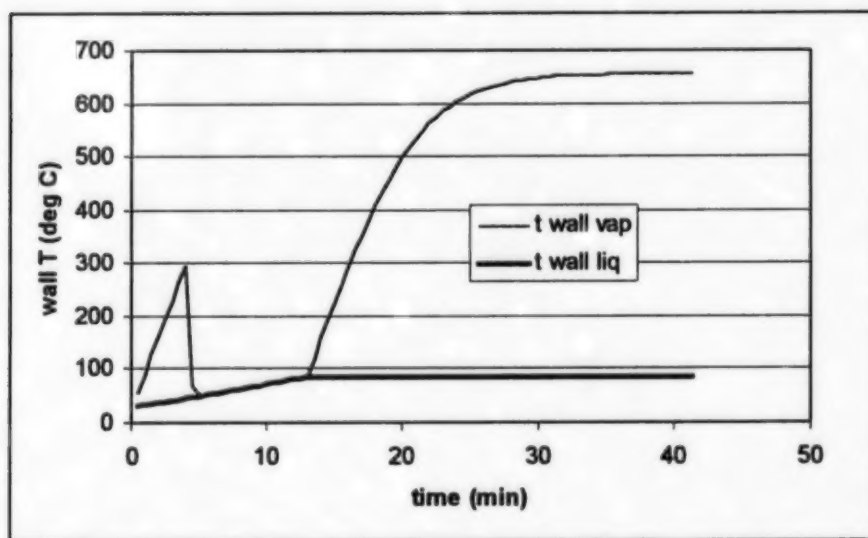


Figure 3-4: Predicted Wall Temperature vs Time (TMID)

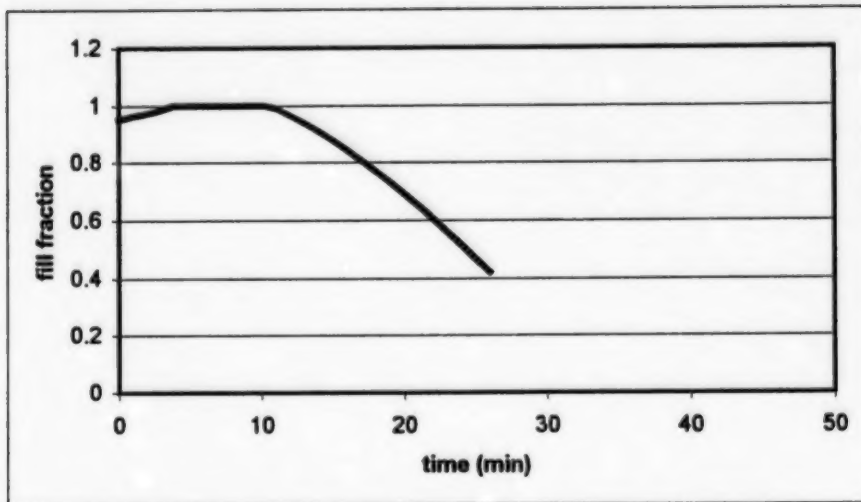


Figure 3-5: Predicted Fill vs Time (AFFTAC)

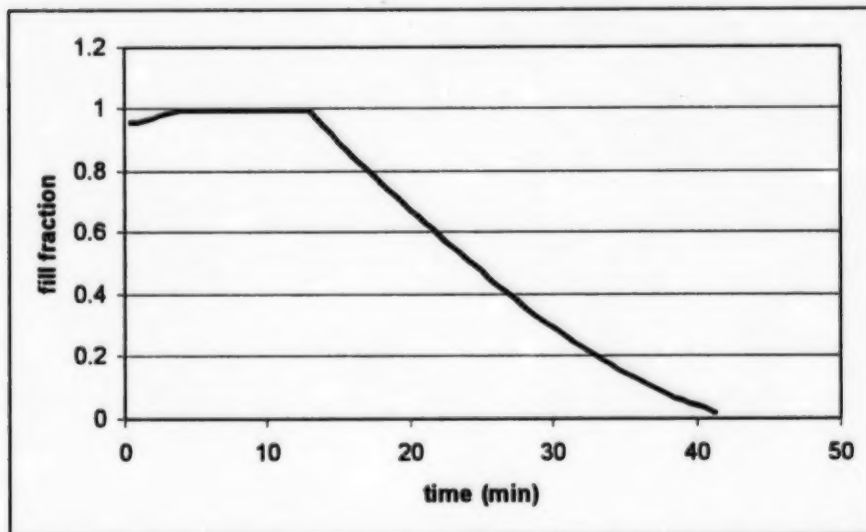


Figure 3-6: Predicted Fill vs Time (TMID)

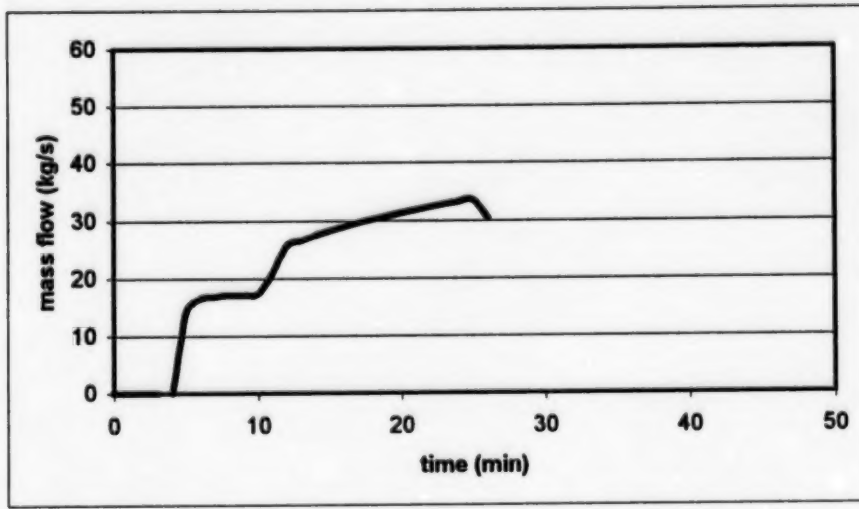


Figure 3-7 Predicted PRV Flow vs Time (AFFTAC)

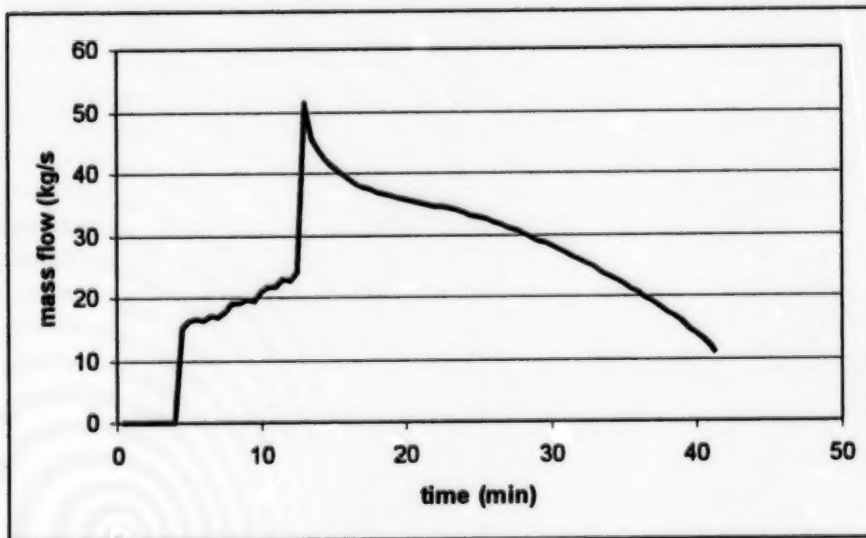


Figure 3-8: Predicted PRV Flow vs Time (TMID)



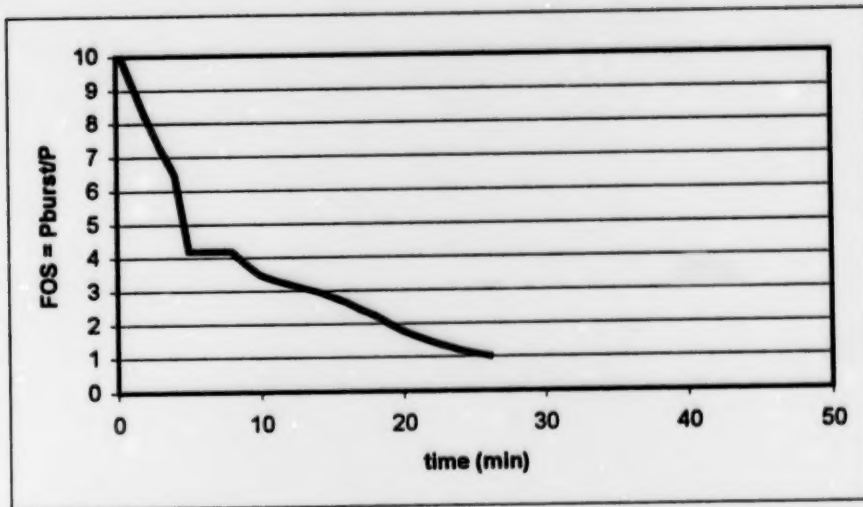


Figure 3-9: Predicted FOS vs Time (AFFTAC)

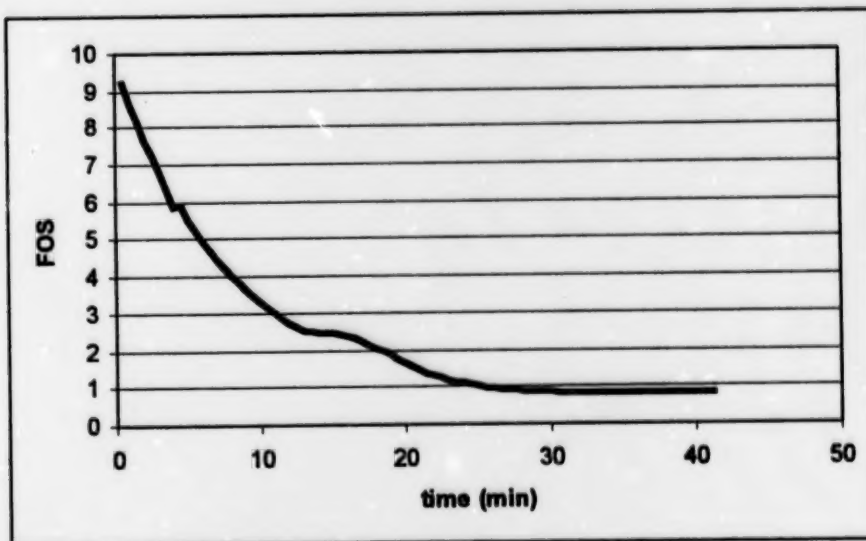


Figure 3-10: Predicted FOS vs Time (TMID)

## 4 Thermal Protection Defect Analysis Results

This section shows the results of computer simulations of tanks with thermal insulation defects exposed to pool and torch fires. Two different models were used. The first, AFFTAC, is the FRA standard computer model for evaluating thermal protection systems. The second code, TMID, was developed for this study to account for partial insulation defects.

The results about to be presented are preliminary. Further validation is necessary to confirm the accuracy of these predictions.

### 4.1 AFFTAC Simulations

The AFFTAC model is described in detail by Johnson (1998).

The AFFTAC model cannot be used to study localized insulation defects as it currently exists. However, it can be used to study the limiting cases of a well protected tank and a thermally protected tank where all of the insulation has been lost under the steel jacket. In other words, 0% and 100% insulation defect.

#### 4.1.1 0% Insulation Defect

In this case we will consider a tank with insulation that just meets the DOT plate test criteria. Johnson (1995) stated that such an insulation would have a conductance of about 4 Btu/hr ft<sup>2</sup> °F (i.e. 22.7 W/m<sup>2</sup> K).

The test case has the following inputs:

- 112J340W tank car
- propane
- thermal protection with constant conductance of 22.7 W/m<sup>2</sup> K (4 Btu/hr ft<sup>2</sup> °R)
- tank capacity 33000 gal
- tank diameter 119 inches
- wall thickness 0.69 inches (17.5 mm)
- 90% full of propane
- 60 °F initial temperature (15.6 °C)
- 25800 scfm PRV with start-to-discharge pressure at 280.5 psig with 308.6 psig flow rating pressure
- surface emissivity 0.9
- TC 128 steel assumed

The results of the pool fire simulation are as follows:

**Table 4-1: Results of AFFTAC Simulation for Pool Fire Exposure of Thermally Protected Tank with 0% Defect (22.7 W/m<sup>2</sup> K average conductance).**

Time (min)	P (psi)	P burst (psi)	T wall (°C)	Fill (%)
100	258	780	398	47
150	243	625	492	11
174 empty	234	517	547	0
200	232	326	643	liquid empty
218 failure	232	232	691	liquid empty

As can be seen from the above, the tank survives well after the 100 minute requirement. This is because the assumed insulation properties meet the plate test standard of keeping the wall temperature below 427° C (800° F) for 100 minutes.

The reader should note the following:

- The pressure is decreasing in the tank because as the liquid level drops the required PRV flow is decreasing and in the AFFTAC model this results in a lower tank pressure and lower hoop stress. This may not happen in reality.
- After the tank empties of liquid the vapour wall temperature rises much more rapidly resulting in tank failure at 218 minutes.

The factor of safety (based on burst pressure) in this simulation at 100 minutes is  $FOS = 780/258 = 3.0$ . In other words, even with insulation that just meets the standard, the tank was three times as strong as needed to pass the 100 minute pool fire simulation. This factor of safety is appropriate to cover some of the uncertainties of the simulation. If this tank were protected with specification ceramic blanket insulation such as Kaowool (see Appendix F) the FOS would have been even higher, in the range of 4.0 to 6.0.

#### 4.1.2 100% Insulation Defect

In this case it is assumed there is no insulation under the steel jacket. Both pool fire and torch fire cases have been considered here. In AFFTAC this case is modelled by choosing a degrading insulation and specifying the time to degrade to be 0.1 minutes. With AFFTAC the model assumes a char (i.e. degraded insulation) residue conductance of 40 Btu/hr ft<sup>2</sup> °R after the insulation is gone. This, therefore, is not really the same as having no insulation in the gap between the tank wall and the jacket.

#### 4.1.2.1 Pool Fire Simulation

With the same tank conditions as noted above (except now the insulation degrades away in 0.1 minutes), and with the tank exposed to an engulfing pool fire with  $T = 816^{\circ}\text{C}$ , the tank empties of liquid in about 88.5 minutes and fails at 94.3 min. The results are summarized in the following table.

Table 4-2: Results of AFFTAC simulation for pool fire exposure of thermally protected tank with 100% defect).

Time (min)	P (psi)	P burst (psi)	T wall ( $^{\circ}\text{C}$ )	Fill (%)
88.5 (empty)	233	308	653	0
94.3 (failure)	231	231	692	0

By the letter of the standard this tank just fails the 100 minute pool fire test (it failed by about 6%). This means that if there was only 90% defect this model would result in a pass conclusion. This conclusion leaves no factor of safety.

#### 4.1.2.2 Torch Fire Simulation

The above case was repeated but with a  $1204^{\circ}\text{C}$  torch fire applied to a  $1.2\text{ m} \times 1.2\text{ m}$  portion of the tank (as per AFFTAC assumptions). The results of this simulation are as follows:

at 30 minutes

P = 94 psig

P burst = 371 psig

FOS = 3.9

fill = 90%

T wall =  $620^{\circ}\text{C}$  ( $1149^{\circ}\text{F}$ )

As can be seen, AFFTAC predicts that this tank does not even come close to failure even with 100% insulation defect ( $\text{FOS} = 371/94 = 3.9$ ). The reader should note that the small torch exposure does not result in a pressure rise in this simulation. However, even if there was a pressure rise to the PRV std pressure the tank would still not fail this simulated 30 minute torch test.

#### 4.1.3 AFFTAC Conclusions

Based on the AFFTAC model, a thermally protected tank (type 112J340W with 17.5 mm wall, 280.5 psig std pressure, propane, 90% full, TC 128 steel) with thermal

protection (13 mm insulation with steel jacket) with an average conductance of 22.7 W/m<sup>2</sup>K will survive a 816 °C engulfing pool fire for 100 minutes with a factor of safety (FOS = burst pressure/pressure) at 100 minutes of about 3.0. The same tank with all of the insulation lost under the steel jacket will fail the same simulation test because tank failure is predicted at 94 minutes into the test.

With AFFTAC, the pool fire appears to be the determining test for insulation defects. The torch fire simulation resulted in the tank being far away from failure at the 30 minute time limit.

The AFFTAC simulation results should be interpreted in the following way.

- Tanks with large areas of insulation missing under the steel jacket could come dangerously close to failure within 100 minutes when exposed to a pool fire.
- The torch fire test does not appear to be the determining factor with insulation deficiencies under a steel jacket, provided we accept the following AFFTAC modelling assumptions:
  - torch exposure is minor (<1% of tank surface)
  - torch heat flux is about 116 kW/m<sup>2</sup> (large propane torches could be 200 kW/m<sup>2</sup> or more)
  - tank pressure is well below the PRV std pressure
  - tank fill level is high (90%)

#### **4.2 TMID Simulations**

The AFFTAC model suggested that a thermally protected 112 type tank with propane with 100% insulation defect (just steel jacket) would "just" fail the pool fire simulation test. Therefore by AFFTAC a tank that has slightly less than 100% defect (say 90%) could pass. However, accepting 90% defect would not be prudent as it includes no factor of safety to account for simulation uncertainties.

The questions to be answered now include:

- What happens if we apply some reasonable factor of safety?
- What amount of defect is acceptable?

The analysis about to be presented uses the concept of FOS to identify acceptable levels of insulation defect.



#### 4.2.1 Torch Fire Simulation

It was shown earlier using AFFTAC that the torch test is not the determining factor for a tank with steel jacket. In this section TMID simulation results are shown for a torch fire simulation of a tank with insulation defects. The test case is a 112 car with propane as follows:

112J340W type car with thermal protection  
propane  
initial fill = 0.90  
initial T = 15.6° C  
wall thickness = 17.5 mm  
13 mm of insulation  
PRV pop pressure P = 2.0 MPa (1.03 x 280.5 psig)  
TC 128 steel  
tank emissivity = 0.9  
insulation defect from tank top to 90 degrees around side

In this case the insulation defect runs the entire length of the tank on one side. All protected areas have conductance 22.7 W/m<sup>2</sup> K (4 Btu/hr ft<sup>2</sup> F). The simulated torch is applied to a ring that goes all around the tank so that the torch heats all possible surfaces (vapour space protected and unprotected, liquid space protected and unprotected).

The TMID model was run with the following torch conditions:

temperature 1204° C  
heat flux factor 0.45 (torch emissivity)  
exposure area 1% of tank

The following was predicted for the above tank after 30 minutes of torch exposure.

P = 0.7 MPa  
P burst = 2.1 MPa  
FOS = 3.0  
T wall = 652° C  
Fill = 90%

This result is somewhat different than that from AFFTAC, but with the same conclusion. The predicted wall temperature is higher by about 35 °C and this results in a reduced burst pressure by about 18%. This discrepancy between AFFTAC and TMID for the torch case is due to the fact that AFFTAC assumes a conductance of 40 BTU/hr ft<sup>2</sup> °R) when all the insulation is gone under the jacket. In fact, if there is no insulation the effective conductance is higher than this due to the effects of thermal radiation.

In any event this confirms that the torch fire does not appear to be the determining case (assuming 1% exposure and other AFFTAC torch assumptions). If we assume 30% exposure the following result is obtained at 30 minutes:

P = 1.07 MPa  
P burst = 2.2 MPa  
FOS = 2.1  
T wall = 642° C  
Fill = 99%

This suggests the tank will be near liquid full at 30 minutes and therefore the rising liquid is cooling the vapour space wall. Once again the result suggests that the torch is not the limiting case. However, we should note that the predicted tank pressure of 1.07 MPa is probably incorrect because of the effects of liquid temperature stratification. If the tank did pressurize because of liquid temperature stratification then the  $FOS = 2.2/1.8 = 1.2$

Let us repeat this run with a low liquid fill level of 80%. At 30 minutes, the outcome is:

P = 1.05 MPa  
P burst = 2.1 MPa  
T wall = 649° C  
Fill = 83%

Once again the tank passes the standard torch test even with 30% exposure, suggesting that this torch test will not be the determining test for insulation defects. Note that this conclusion only applies if we use the torch heat flux as defined earlier. A large torch from a burning PRV flare will be more intense than the torch used in the steel plate tests. This is because of the scale of the torch. Larger torches will behave more like an engulfing fire but with a higher flame temperature.

Let us simulate this case with the following assumptions (all other data as before) :

torch temperature 1204° C  
torch emissivity 1.0 (rather than the 0.45 used earlier)  
30% exposure  
tank fill 90%

Note that this torch will heat the steel plate up much faster than required by the standard (i.e. 427° C in 4 minutes). The result is that the tank fails after about 10 minutes, with the following details:

P = 0.88 Mpa  
P burst = 0.88 MPa  
T wall = 749 °C

Fill = 96%

As can be seen from this example, the exact torch details determine the result. If we use the DOT standard torch then the tank with defective insulation passes the test. If we use a torch that more closely simulates a credible real-world torch event (i.e. burning PRV flare from an overturned tank) then the tank with defective insulation will probably fail the test.

**Table 4-3** summarizes the torch simulation results.

**Table 4-3: Summary of TMID torch results**

	<b>1% Exposure 1204° C torch emm = 0.45</b>	<b>30% Exposure 1204° C torch emm = .45</b>	<b>30 % Exposure 1204° C torch emm = 1.0</b>
Outcome	pass at 30 minutes	pass at 30 minutes	fail at 10 minutes
P MPa	0.7	1.07	0.88 at fail
P burst MPa	2.1	2.2	0.88 at fail
T wall °C	652	642	749 at fail
FOS	3.0	2.1	1.0 at fail
Fill	90 %	99%	96% at fail

#### 4.2.2 Pool Fire Simulation

It was shown earlier that the torch fire simulation test may not be the determining factor for a tank with steel jacket if we use the DOT standard torch conditions. In this section simulation results are shown for pool fire simulations of tanks with insulation defects. The test case is a 112 car with propane as follows:

112J340W type car with thermal protection  
propane  
diameter 3.0 m  
length 17.3 m  
initial fill = 0.90 (to give 99% full at 43° C)  
initial T = 15.6° C  
wall thickness = 17.5 mm  
13 mm of insulation  
PRV limited tank pressure P = 2.0 MPa (1.03 x 280.5 psig)  
TC 128 steel  
tank emissivity = 0.9  
pool fire T = 816° C  
fire emissivity 1.0  
tank fire exposure 100%

In these cases the insulation defect runs the entire length of tank on one side. All protected areas have conductance  $22.7 \text{ W/m}^2 \text{ K}$  ( $4 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$ )

The first case we will consider is that of a 112 tank with a negligible defect that runs the length of the tank at the top (defect spans from 0 to 1 degree around the tank side, i.e. defect area  $< 0.3\%$  of tank surface). The results of this simulation are shown in Figure 4-1 to Figure 4-5.

The results show that TMID is in good agreement with AFFTAC for the case of a well insulated tank. The well insulated tank empties at about 170 minutes and by AFFTAC would fail sometime after that. In other words the well insulated tank far exceeds the pool fire simulation test. The wall temperature in the well insulated areas stays below  $427^\circ \text{C}$  for over 100 minutes and therefore passes the old plate test standard. At  $427^\circ \text{C}$  the wall is still very strong and the tank is far from failure (i.e.  $\text{FOS} = 5$ ). However, the small area where the insulation is defective reaches a temperature of  $580^\circ \text{C}$  at 100 minutes. At this temperature the FOS is very close to the suggested limit of 1.6 and therefore the tank is very near failure based on this criterion.

Once again, the FOS plot deserves comment. As can be seen in the plot the FOS drops rapidly when the fire starts and drops to  $\text{FOS} = 2.0$  at about 70 minutes. The FOS then drops very slowly from 2.0 to about 1.5 at 150 minutes. This shows that a small error in the prediction of FOS can lead to a very large error in time to failure prediction. This again supports the idea of applying a significant FOS.

Now let us vary the area of defective insulation to see how the tank condition varies. Recall that the defective insulation is assumed to be areas where there is no insulation material under the steel jacket. The following table summarizes the results from simulations where the defect size is varied. Once again, we use a  $\text{FOS} = 1.6$  (recall that  $\text{FOS} = (\text{burst pressure})/(\text{tank pressure})$ ).

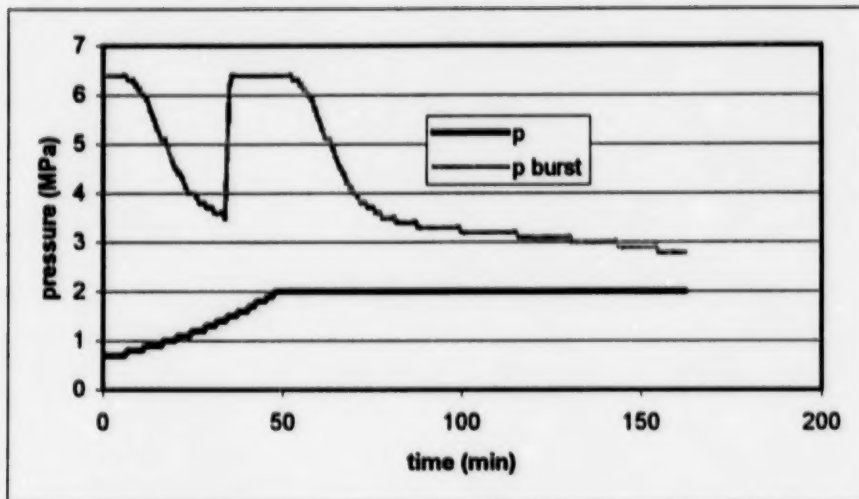


Figure 4-1: Pressure and Burst Pressure vs Time (TMID, insulated tank with small defect at tank top)

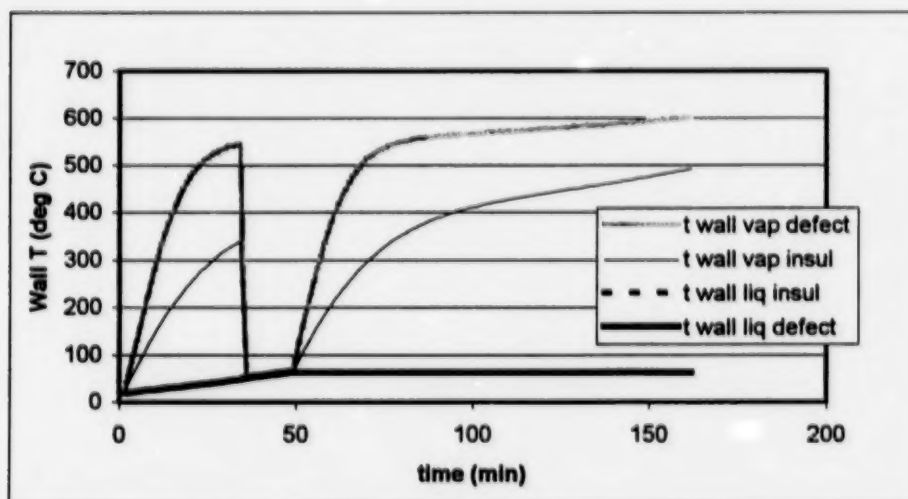


Figure 4-2: Wall Temperatures vs Time (TMID, insulated tank with small defect at tank top)



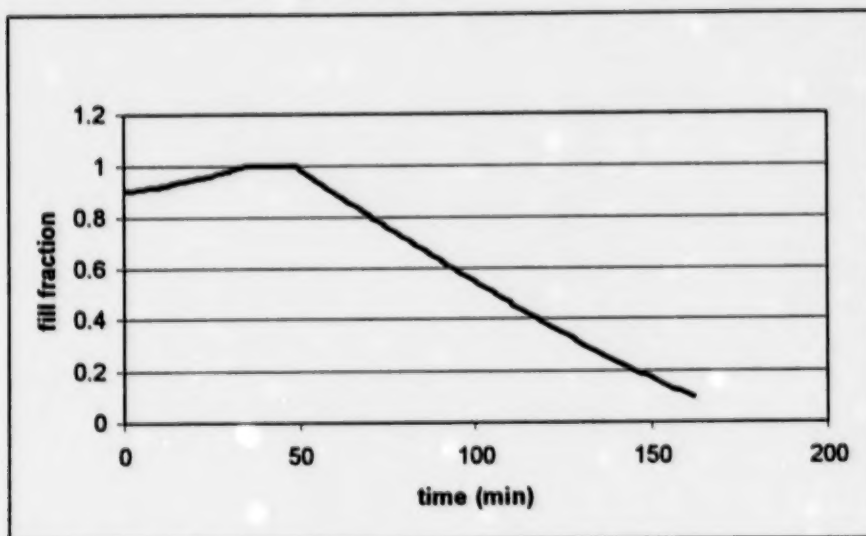


Figure 4-3: Fill vs Time (TMID, insulated tank with small defect at tank top)

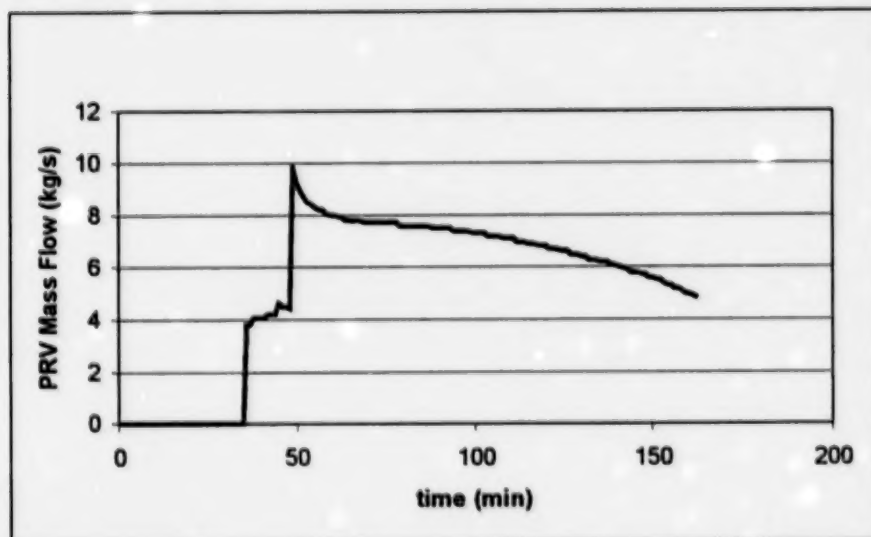


Figure 4-4: PRV Mass Flow vs Time (TMID, insulated tank with small defect at tank top)

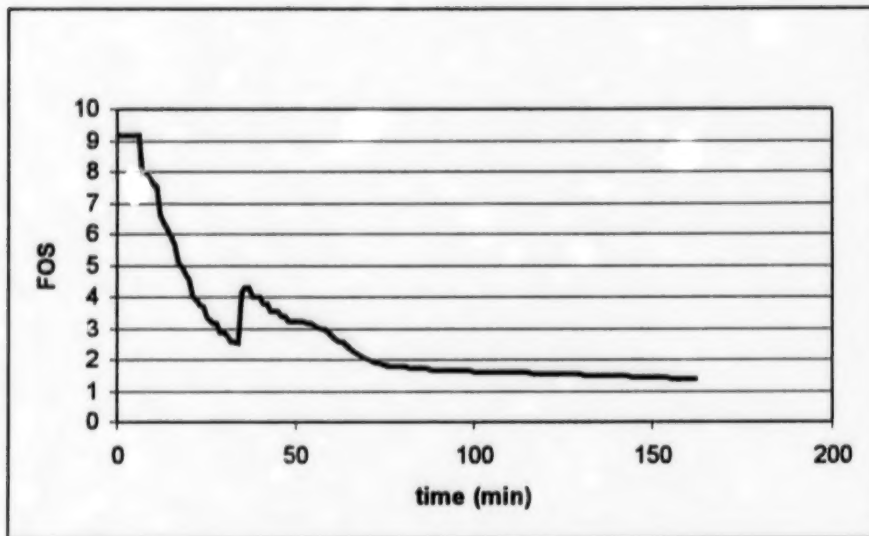


Figure 4-5: FOS based on Defect Area Temperature vs Time (TMID, insulated tank with small defect near tank top)

Table 4-4: Summary of Pool Fire Simulation Results (FOS = 1.6, insulation conductance 22.7 W/m<sup>2</sup> K)

Defect area	Fail time with FOS = 1.6	Wall T at fail	Liquid fill at fail
from top to 10 deg 3% of area	101.3 minutes	570	52%
top to 20 deg 6%	97.5	570	54%
top to 30 deg 8%	93.6	570	56%
top to 90 deg 25%	75	570	62%
top to 180 deg 50%	66	570	55%

Therefore, if we use a factor of safety of 1.6, and we assume insulation with constant conductance of  $22.7 \text{ W/m}^2\text{K}$  everywhere else then we can only accept defects that cover up to about 4 % of the tank surface. Recall that this conductance represents insulation that would just pass the plate test standard.

Now let us consider the case of good quality ceramic blanket insulation such as Kaowool (see Appendix F).

Table 4-5: Summary of Pool Fire Simulation Results using a FOS = 1.6 with Kaowool Properties (density  $72.2 \text{ kg/m}^3$ ).

Defect area	Fail time with FOS = 1.6	Wall T at fail	Liquid fill at fail
from top to 10 deg 3% of area	184 minutes	570	48%
top to 60 deg 17%	115	570	54%
top to 80 deg 22%	102	570	68%
top to 90 deg 25%	98.4	570	67%
top to 100 deg 28%	95	570	66%
top to 180 deg 50%	77	570	57%

If we use a factor of safety of 1.6, and we assume 13 mm of Kaowool ceramic blanket insulation everywhere else then we can accept defects that cover up to about 23 % of the tank surface.

#### 4.2.3 Sensitivity Study Results

Let us now study how the previous results are affected by changes in important variables. We want to know how the results are affected by:

- i) effect of FOS
- ii) initial fill
- iii) defect position
- iv) PRV limited tank pressure
- v) tank surface emissivity
- vi) commodity

### i) Effect of FOS

First let us look at the results if we use FOS = 1.0. **Table 4-6** gives a summary of results with the baseline case (propane, D = 3m, L = 17.4 m, 90% full, 2 MPa PRV, insulation conductance 22.7 W/m<sup>2</sup>K, etc.).

**Table 4-6: Summary for FOS = 1.0**

Defect Top (deg)	Defect Bottom (deg)	Fail/empty Time (min) (FOS = 1)	FOS at Time	Defect Vapour Wall T (°C)	Liquid T (°C)	Tank Fill	Lading Mass (kg)
0	0	173 empty	-	-	60	.02	6900
0	30	160 empty	1.19	631	60	.02	6900
0	60	150 empty	1.13	641	60	.02	6900
0	90	140 empty	1.06	651	60	.02	6900
0	120	129 fail	1	659	60	.033	7154
0	180	109 fail	1	659	60	.029	7360

The simulation suggests that even with 50% defect the tank will survive the 100 minute simulation if FOS = 1.0 is applied. With smaller defects the tanks go empty before failure is indicated. Note that TMID stops the simulation when the tank has 2% liquid by volume (i.e. liquid empty). As can be seen from the table, when the tank is empty it is dangerously near failure.

Now let us vary the FOS from 1.2 to 1.7 and find the defect area needed for failure at 100 minutes. The results are shown in **Table 4-7**. Note that these results apply to the case of insulation with constant conductance of 22.7 W/m<sup>2</sup>K.

**Table 4-7: Summary of Pool Fire Simulation Results using Varying FOS, (112 tank, propane, 2 MPa PRV, 17.5 mm wall, 90% full, 16 C initial T)**

FOS	Allowable Defect Area in % of Tank Surface	Fail Time with FOS	Wall T at Fail	Fill at Fail
1.7	0 %	93 minutes	542	62%
1.6	4 %	100	570	53%
1.5	17%	100	585	43%
1.4	28%	100	600	36%
1.3	42%	100	615	22%
1.2	53%	100	630	12%

The selected FOS has a dramatic effect on the allowable defect area. As noted earlier, it is suggested that FOS = 1.6 based on fire, PRV and material strength considerations. If, for example, the fire variability is ignored then a FOS of 1.4 is reasonable and this would allow up to 28% defective insulation.

ii) initial fill

Let us fix the defect at 0-90 deg (25% defect) and vary the tank initial fill from 90% to 20%. All other factors remain the same including FOS = 1.6.

Table 4-8: Summary of Pool Fire Simulation Results Using a FOS = 1.6, with Tank Initial Fill Varied from 20 to 90%. (112J340W tank, propane, 816 °C pool fire).

Initial Fill	Fail Time with FOS = 1.6	Wall T at Fail	Liquid Fill at Fail
90%	75 min	572 °C	62%
80%	56	572	76
50%	38	578	56
20%	34	579	17

Fill plays an important roll in the time to failure. This is because of the heat transfer assumptions used in the model. AFFTAC assumes the liquid surface acts as a heat sink to cool the vapour space wall. Low fill levels result in less cooling of the vapour space wall and therefore higher wall temperatures are predicted.

The following table shows the effect of varying defect area when the tank is initially filled to 80%.

Table 4-9: Summary of Pool Fire Simulation Results using an Initial Fill of 80% with Constant Insulation Conductance of 22.7 W/m<sup>2</sup>K.

Defect Area	Fail Time with FOS = 1.6	Wall T at Fail	Liquid Fill at Fail
from top to 10 deg 3% of area	86 minutes	570	60%
top to 60 deg 17%	58	570	80%
top to 90 deg 25%	54	570	79%

As can be seen, no defect is allowed with this case.



iii) defect position

Let us now hold the size of the defect the same but move it around the side of the tank. The FOS = 1.6 and all other factors are held constant (fill = 90%).

Table 4-10: Summary of Pool Fire Simulation Results using an FOS = 1.6, with Position of Defect Varied Around Side of Tank (112J340W tank, propane, 816° C pool fire)

Defect Area	Fail Time with FOS = 1.6	Wall T at Fail	Liquid Fill at Fail
from top to 90 deg	75 min	572 °C	61%
from 20 to 110 deg	77	572	58
from 40 to 130 deg	79	572	54
from 60 to 150 deg	85	572	46
from 80 to 170 deg	104	572	27

From above we see that the worst defect position is near the tank top. This is what we would expect. If the defect is near the tank bottom we can increase the allowable defect to over 25% according to this simulation.

The problem with applying this conclusion is that a tank may roll over in an accident. Therefore if a defect is near the bottom of a tank it could be as dangerous as one near the tank top.

iv) PRV limited tank pressure

In TMID the tank pressure is assumed to be held at 103% of the PRV start to discharge pressure by the PRV. So far this pressure has been set to 2.0 MPa. The following results apply for the case where the PRV controls the tank pressure to be 1.8 MPa (263 psig). As before the other tank conditions are:

112J340W type car with thermal protection  
propane  
diameter 3.0 m  
length 17.3 m  
initial fill = 0.90 (to give 99% full at 43 °C)  
initial T = 15.6 °C  
wall thickness = 17.5 mm  
13 mm of insulation  
TC 128 steel  
tank emissivity = 0.9  
pool fire T = 816° C  
fire emissivity 1.0  
tank fire exposure 100%

**Table 4-11: Summary of Pool Fire Simulation Results using a FOS = 1.6 with Reduced PRV Limited Tank Pressure (P = 1.8 MPa).**

<b>Defect Area</b>	<b>Fail Time with FOS = 1.6</b>	<b>Wall T at Fail</b>	<b>Liquid Fill at Fail</b>
from top to 10 deg 3% of area	146 minutes	594	19%
top to 20 deg 6%	141	594	21%
top to 60 deg 17%	115	594	31%
top to 80 deg 22%	101	594	38%
top to 90 deg 25%	95	594	41%

As can be seen a reduced tank pressure has a very significant effect on time to failure. A lower pressure means a lower stress and this means a higher wall temperature is needed to fail the tank. A higher wall temperature requires a lower tank fill condition, which takes more time.

This small change in tank pressure increased the allowable defect from 4% to about 23% for the assumed conditions.

#### v) tank surface absorptivity

So far, all computer runs have assumed a tank surface emissivity/absorptivity of 0.9. As noted earlier in this report this value of emissivity is considered appropriate for the materials considered here. This is in contrast to AFFTAC, that recommends the use of 0.8. The following results show what happens when emissivity is changed from 0.9 to 0.8. All other factors are as before.

As can be seen the reduced emissivity causes a lower heating rate by the fire and this increases the time to tank predicted failure. With this change the allowable defect changes from 4% to about 15%.

**Table 4-12: Summary of Pool Fire Simulation Results Using a FOS = 1.6 with Reduced Tank Surface Emissivity of 0.8.**

<b>Defect Area</b>	<b>Fail Time with FOS = 1.6</b>	<b>Wall T at Fail</b>	<b>Liquid Fill at Fail</b>
from top to 10 deg 3% of area	117 minutes	570	41%
top to 20 deg 6%	114	570	43%
top to 50 deg 14%	101	570	50%
top to 90 deg 25%	87	570	55%

It should be noted that surface emissivity plays a major role because of its effect on the radiation between the tank wall and the steel jacket when the insulation is missing. The heat flux between the jacket and the wall is calculated from the following:

$$q = \frac{\epsilon}{2 - \epsilon} \sigma (T_j^4 - T_w^4)$$

where,

q = heat flux W/m<sup>2</sup>

T<sub>w</sub> = wall temperature

T<sub>j</sub> = jacket temperature

ε = surface emissivity

σ = Stefan-Boltzman constant

With the above equation the surface emissivity has a strong effect on q.

vi) commodity

So far all computer runs have been conducted using pure propane as the commodity. Other commodities of interest include:

- i) anhydrous ammonia for 105 and 112 type cars
- ii) chlorine for 105 type cars

The different commodities will affect the following:

- i) pressurization rate
- ii) thermal expansion of liquid
- iii) PRV flow and time to empty

The specific heat of the lading determines how quickly it will heat up. The latent heat of vaporization determines how quickly the tank will empty through the PRV. The worst case is where the lading empties quickly from the tank thereby exposing more wall to the vapour space.

**Table 4-13** shows some examples of commodities and their properties. In this study we were asked specifically to consider propane, chlorine and anhydrous ammonia. As can be seen from the table ammonia has a much higher heat of vaporization than propane and therefore will boil off much more slowly than propane. Chlorine is much more dense than propane and this too increases the time for the chlorine to leave the tank through the PRV.

**Table 4-13: Some Data on Different Commodities**

Commodity	Tank Car Type	Density (kg/m <sup>3</sup> )	Specific Heat of Liquid C <sub>p</sub> (kJ/kg K)	Heat of Vaporization h <sub>fg</sub> (kJ/kg)	critical pressure (bar)	critical temperature (K)
propane	105, 112	506	3.1 at 50 °C	428	42.7	370
ammonia	105, 112	681	4.8 at 25 °C	1357	112.8	406
chlorine	105	1400		288	77	417
propylene	105, 112	520		437	46.2	365
n-butane	105, 112	582	2.3 at 0 °C	385	38	425
ethylene	113	567		484	51.2	283
ethylene oxide	105, 111	870	2.0 at 20 °C	579	71.9	469

**Table 4-14** shows AFFTAC simulation results for propane and anhydrous ammonia in 112J340W type tanks (AFFTAC does not consider chlorine). The ammonia is released from the tank much more slowly due to its higher density, specific heat and heat of vaporization. Therefore this shows that propane is the design worst case for thermally protected 112 type tanks.

The 105 cars that carry chlorine and anhydrous ammonia are insulated tanks that must also meet thermal protection requirements. The conductance required to meet the thermal insulation standard is much smaller than that required for thermally protected tanks. Therefore, the thermally insulated tank should pass the torch and pool fire simulation with more allowable defect than the thermally protected tank. This is true only if the thermal insulation used in the tank can withstand the high fire temperatures for the required length of time. It also assumes that the tank PRV can handle the increased flow caused by the insulation defects. It should be noted that tanks with thermal insulation may have relatively small PRVs if they are sized using the AAR sizing formula. If a thermally insulated tank with a small PRV has large insulation defects then this could lead to

excessive pressure buildup in a fire accident. This has not been investigated in detail in this report.

**Table 4-14: Comparison of Different Commodities with AFFTAC (112 tank, 17.5 mm wall, 90% initial fill, initial temperature 16 °C, no insulation under jacket – i.e. 100% defect)**

Commodity	Liquid Empty Time	Fail Time	Burst P at 100 min	P at 100 min	FOS at 100 min	Wall T at 100 min	Fill at 100 min
propane	90	97	210	210	< 1	708 °C	liquid empty
anhydrous ammonia	not empty after 200 min	no fail	541 psi	267 psi	2.03	534 °C	0.74

#### 4.2.4 Special Considerations

It should be noted that the wall temperature and its chemical effects on the commodities have not been studied in detail.

For example, it is known that if chlorine comes in contact with steel at above 215 °C, intense local heating will take place and the steel can ignite (see TIPS manual for chlorine, Environment Canada, 1984). This fact alone suggests insulation defects should not be allowed on 105 cars that carry chlorine.

Insulated 105 cars include 102 mm of insulation (51 mm fibre glass and 51 mm of ceramic blanket) covered by a steel jacket. This insulation system provides excellent protection from fires and by TMID estimates it will keep the wall temperature below 215 °C in the vapour space for over 100 minutes. However, if there is a significant insulation defect in the vapour space the wall temperature there could exceed 215 °C in under 10 minutes (see Appendix E for simulation results). This suggests that chlorine cars may not tolerate any insulation defects.

#### 4.2.5 Summary of Sensitivity Study

The following table summarizes the results of the sensitivity study.



Table 4-15: Summary of Sensitivity Study

Variable Changed	Change	Effect on Allowable Defect	Comment
insulation properties	change from constant conductance of 22.7 W/m <sup>2</sup> K to actual Kaowool properties	increase from 4% to 23%	real-world ceramic blanket insulation probably has properties in this range
FOS	change FOS from 1.6 to 1.4	increase from 4% to 28%	
initial fill	change initial fill from 90% to 80%	decrease from 4% to 0%	real world fill levels are in the range of 80-90%
defect position	move defect from tank top to tank bottom	increase from 4% to 25%	not relevant because tank can roll over in an accident
PRV limited tank pressure	change from 2.0 MPa to 1.8 Mpa	increase from 4% to 22%	
surface emissivity	0.9 to 0.8	increase from 4% to 15%	real-world tank surfaces are probably around 0.9
commodity	propane to ammonia	increase from 4% to 50%	propane appears to be worst case due to its rapid release rate



## 5 Analysis of Thermal Insulation Systems with Defects

Thermal insulation systems are typically installed to insulate the commodity from normal ambient conditions. These systems may also be needed for thermal protection from fires.

### 5.1 Thermal Insulation Systems

In general if a pressure tank-car requires thermal it must meet the following requirement.

*If insulation is a specification requirement, it shall be of sufficient thickness so that the thermal conductance at 15.5 °C (60 °F) is not more than 1.533 kJ/h·m<sup>2</sup>·°C (0.075 Btu/h·ft<sup>2</sup>·°F) temperature differential. If exterior heaters are attached to the tank, the thickness of the insulation over each heater element may be reduced to one-half that required for the shell.*

For tanks that need both thermal insulation and thermal protection, it can be shown that this requirement of conductance of 0.075 Btu/hr ft<sup>2</sup> F far exceeds (by about a factor of 50 if we use 4 Btu/hr ft<sup>2</sup> F as the limit to pass the thermal protection requirement) that needed for the thermal protection requirement. However, for the insulation to pass the thermal protection requirement it must be a high temperature insulation. Common insulation systems include 5 cm of fibreglass insulation (low temperature) and 5 cm of ceramic blanket (high temperature insulation).

If an insulated tank must also be thermally protected, then insulation defects on such tanks will be governed by the limitations specified in the chapter on thermal protection systems.

### 5.2 Insulation Conductance

For the case of thermally insulated tanks a model was developed to calculate the overall average conductance for the tank with and without insulation defects. The model considered the various layers of insulation and the effects of internal and external convective heat transfer. It was assumed that if there was an insulation defect, there would be no insulation present and that stagnant air will fill the insulation defect space. The model included the following details:

- convection and thermal radiation from ambient temperature to outer surface of steel jacket
- conduction through jacket
- conduction through insulation (for no defect) or, conduction and thermal radiation through air space (for defect)

- conduction through tank wall
- convection to liquid

Insulation discontinuities have been discussed earlier in this report.

For pressure cars with thermal insulation the requirement is that the overall conductance cannot exceed  $1.533 \text{ kJ/hr m}^2\text{°C}$  (or  $0.426 \text{ W/m}^2\text{K}$ ). If we ignore the external convective heat transfer coefficient and assume 51 mm of rockwool and 51 mm fibre glass insulation then this would result in a conductance of about  $0.39 \text{ W/m}^2\text{K}$  which better the requirement by about 8%.

If we assume the tank is 90% full then the inside convective coefficient will be high and can be ignored in the conductance calculation. It is important to note that if there is an insulation defect, there will be air in the defect space and this too will act as a good insulator provided the space is closed. However with the thermal insulation gone, thermal radiation from the jacket to the tank wall is possible and this increases the overall conductance. The model was used to estimate the overall conductance for a tank with an insulation defect under the steel jacket. Table 5-1 shows the results of this analysis.

Table 5-1: Estimates of Insulation and Defect Conductance for Various Heat Transfer and Temperature Conditions.

	Normal System Conductance $\text{W/m}^2\text{K}$	Defective System Conductance $\text{W/m}^2\text{K}$	Required
$h = 1 \text{ W/m}^2\text{K}$ $T \text{ diff} = 1 \text{ K}$	0.37	2.7	0.426
$h = 5$ $T \text{ diff} = 1$	0.38	3.3	0.426
$h = 50$ $T \text{ diff} = 1$	0.39	4.5	0.426
$h = 5000$ $T \text{ diff} = 1$	0.39	4.9	0.426
$h = 5$ $T \text{ diff} = 800$	0.39	43.4	0.426

As can be seen from the table, the external convection does not change the insulation conductance very much but it does change the defect conductance significantly. The assumed temperature difference is also important because of the thermal radiation link when the insulation is defective.

Table 5-2 shows that very little defect (< 2%) is acceptable to maintain the  $0.426 \text{ W/m}^2\text{K}$  overall conductance requirement.

**Table 5-2: Estimates of Overall Conductance vs Defect Size and External Convective Coefficient (assuming 1 K temperature difference between surroundings and liquid).**

<b>defect as % of total tank area</b>	<b>overall conductance <math>h = 5 \text{ W/m}^2 \text{ K}</math></b>	<b>overall conductance <math>h = 50 \text{ W/m}^2 \text{ K}</math></b>	<b>required</b>
0	0.38	0.39	0.426
1	0.41	0.43	0.426
2	0.44	0.47	0.426
5	0.52	0.60	0.426
10	0.67	0.80	0.426
50	1.9	1.2	0.426

Note: h value shown is for tank outer surface, thermal radiation is accounted for. No discontinuities (i.e. insulation spacers, structures, etc.) accounted for.

## 6 Detailed Analysis of Insulation Defects

The previous sections showed how insulation defects affect the overall response of the tank-car system to fire impingement or to ambient conditions. This section will now look at the defects in a more detailed way. In this chapter we will consider how defect size affects stress and temperature when a tank is exposed to engulfing fire.

### 6.1 Local Heat Transfer

The local heat transfer analysis was done to see how the size of the defect affects the temperature distribution in the defect.

Figure 6-1 shows the system being analysed. We would expect that as the defect gets smaller its temperature would be reduced by heat conduction to the surrounding protected material. Details of the local heat transfer model can be found in Appendix H.

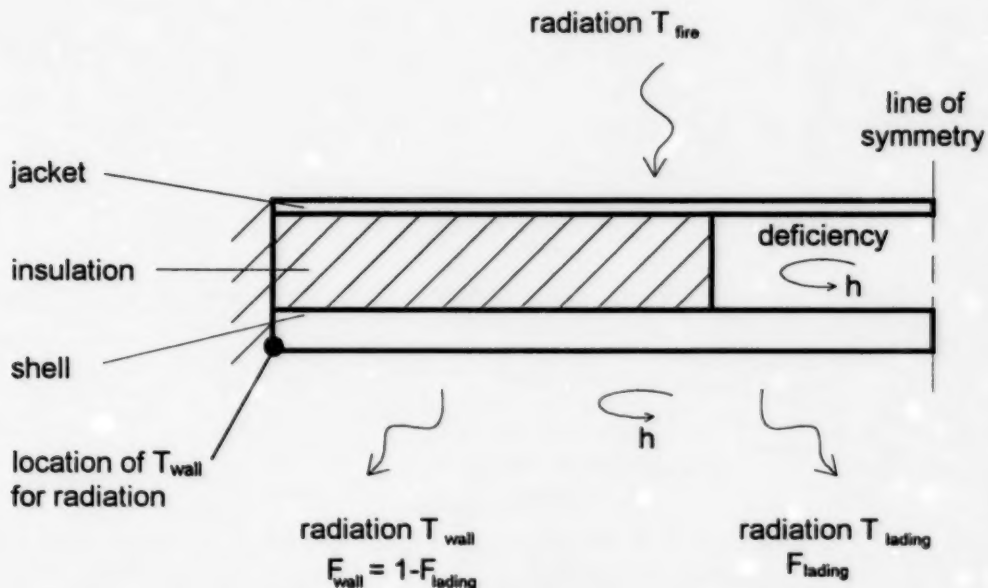


Figure 6-1: Sketch of System in Local heat Transfer Analysis

### 6.1.1 Effect of Defect Size on Defect Temperature Distribution

Figure 6-3 shows how defect size affects the defect maximum temperature. As can be seen from the Figure, the defect size is not important for defects larger than about 0.5 m across for a long strip defect or about a 1 m across if it is an isolated block. In other words, any defect of this size or larger is considered to be "large". As the defect gets smaller than this the temperature decreases because of the cooling effect of the surrounding protected wall.

These results suggest that as the defect gets smaller than about 0.2 m across for a long strip defect, or about 0.4 m across for a isolated block defect the safety margin increases significantly. Therefore defects smaller than this would be considered "small" and therefore a tank covered with a few "small" defects separated by protected material is safer than a tank with one "large" defect.

The next question is: how close together do defects have to be for them to effectively act as a single large defect? This is summarized in Figure 6-2.

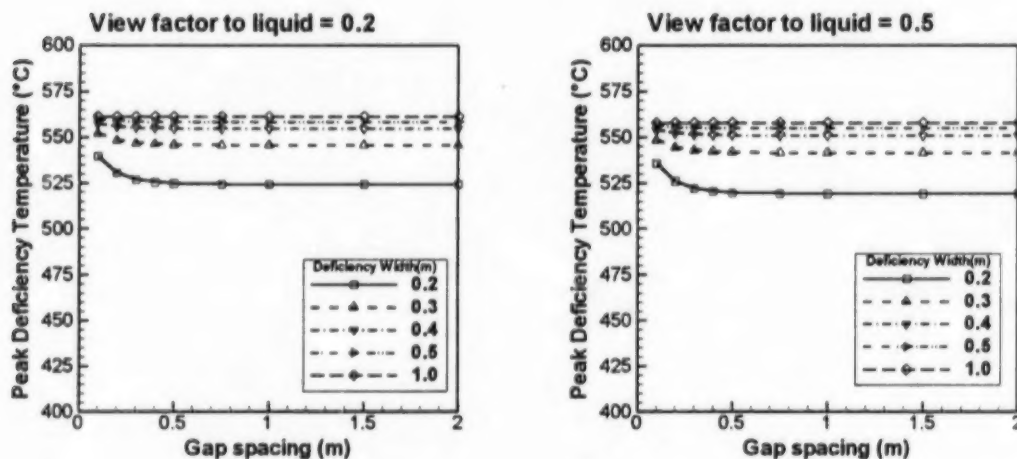


Figure 6-2: Effect of Deficiency Spacing (13 mm insulation)

As can be seen in the Figure, small defects (< 0.2 m for strip defect) should be at least 0.5 m apart to be viewed as separate defects.

## 6.2 Local Stress

As with the heat transfer, the stress in the defect will be affected by the size of the defect for certain defect shapes. If the defect is very small then as the wall area temperature increases it will try to expand. The surrounding cool material will not allow it to expand and as a result compressive stresses will grow to reduce or offset the tensile stresses in the defect wall area. In other words the small defect is offloaded by heating. As the defect gets larger this effect will diminish. As the defect area is offloaded the surrounding protected material takes up the load. It should be noted that the hoop stress will not be offloaded if the defect runs the full length of the tank or the longitudinal stress will not be reduced if the defect extends all the way around the tank circumference.

### 6.2.1 Effect of Defect Size on Defect Stress

A preliminary finite element analysis was conducted to estimate the effects of defect size on the stress distribution in a tank wall. A finite element model was constructed to estimate the stresses in defects (i.e. hot patches in the vapour space wall) surrounded by cooler protected material. Further details of this model can be found in Appendix H.

It is expected that small defects will have reduced stress because the surrounding material will take over the load. This is only true for small block defects. Defects that run the entire length of the tank or the entire circumference will not offload their stress to surrounding material.

Figure 6-4 shows normalized stress (stress at defect centre/ hoop stress in remainder of tank) vs defect temperature and size for isolated block defects. As can be seen the stress is reduced for defect temperatures above about 500 °C. The size of defect does not appear to be important for the size of defects considered (0.2 to 1 m). This stress reduction is not expected to take place in large defects.

This stress applies for a small "block" defect that does not run the length of the tank. For a defect that runs the entire tank length the stress is not reduced because the defect is not surrounded by protected material.

This result suggests that small defects may not be critical. However, this is based on a preliminary analysis and should be used with caution.



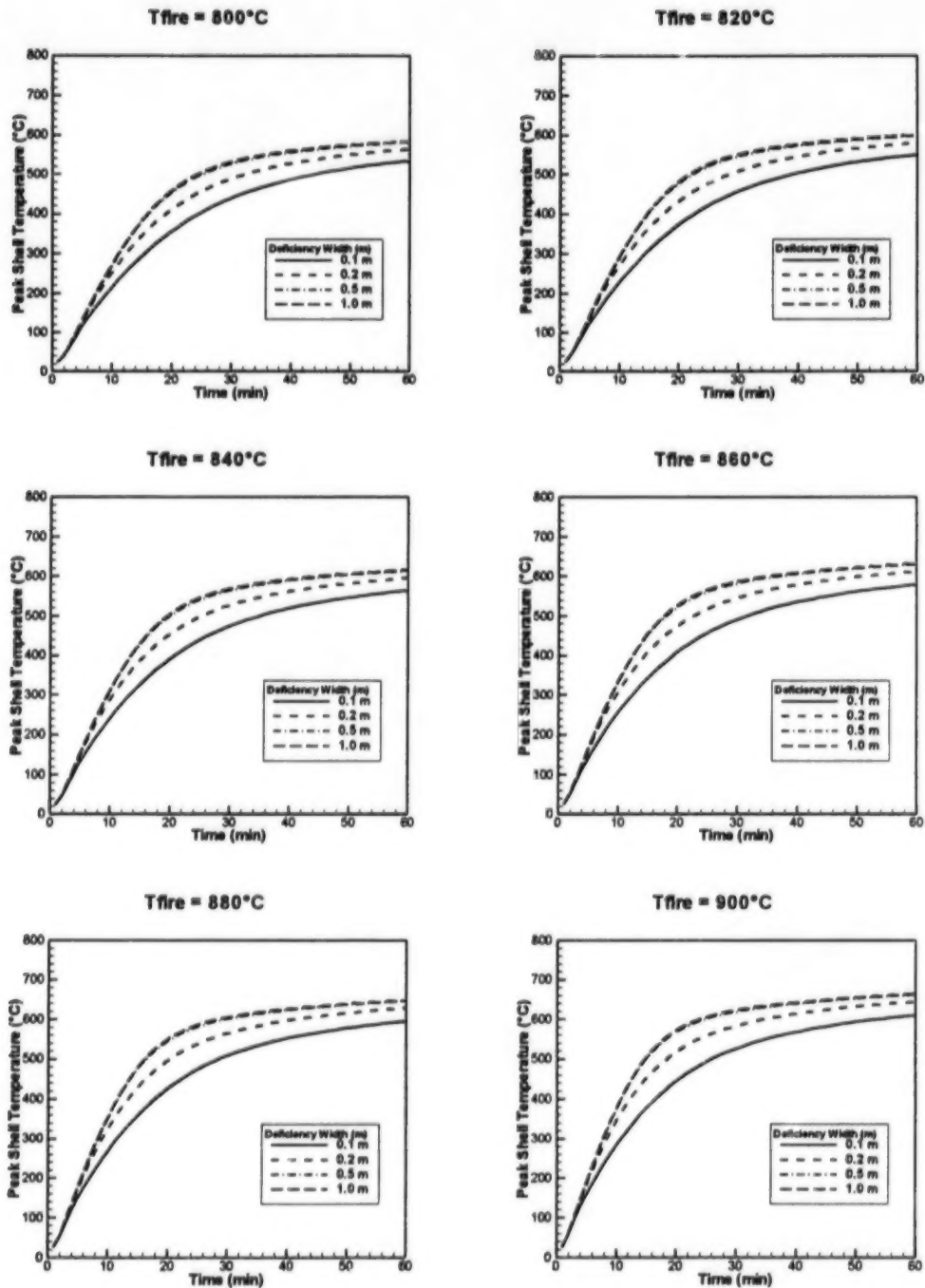


Figure 6-3: Tank Wall Temperature under Defect (13 mm insulation, view factor to liquid  $F = 0.2$ )

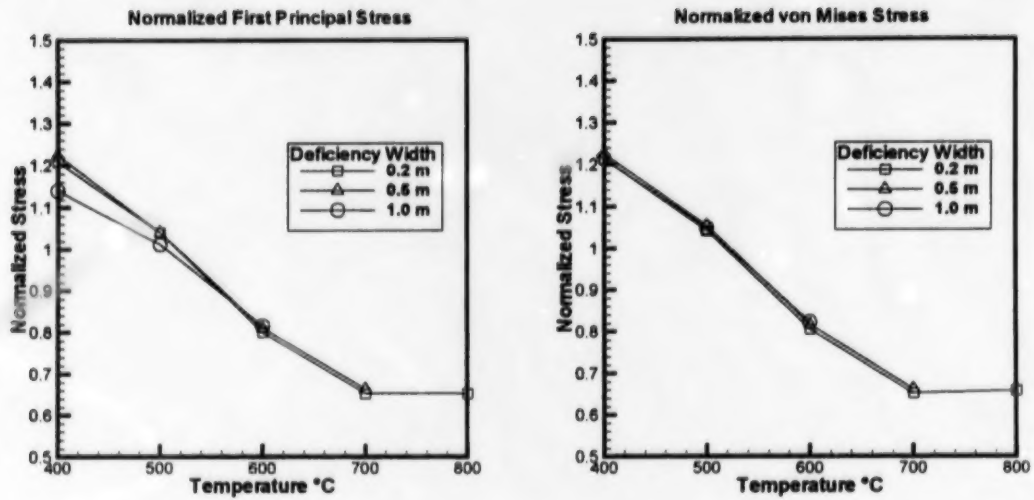


Figure 6-4: Normalized Stress in Centre of Defect Hot Spot for Various Hot Spot Temperatures and Sizes.

## 7 Conclusions and Recommendations

Based on the analysis the following conclusions are made.

### 7.1 Thermally Protected Tanks

A computer model was developed to model a tank-car with insulation defects exposed to engulfing and torch type fires. This model, called TMID (Tank Model with Insulation Defects), is based for the most part on assumptions similar to the FRA AFFTAC 3.0 computer code. It should be noted that this report suggests that the methods used by AFFTAC may not be conservative and therefore there is some uncertainty in applying this type of model to this study.

The TMID model is two-dimensional in that it models the tank as a long cylinder. Insulation defects are modelled as regions where there is no insulation between the steel jacket and the tank wall. Defects are assumed to run the entire tank length on one side of the tank. Defect position is specified by giving the angle from the tank top to the defect top and bottom.

The baseline case considered the following type of tank:

112J340W tank

propane

tank diameter = 3 m, length = 17.3 m

wall thickness = 17.5 mm

insulation conductance 22.7 W/m<sup>2</sup>K

insulation thickness 13 mm

initial fill 90%

initial temperature 15.6 °C

PRV assumed to limit tank pressure to a maximum of 1.03 x start to discharge pressure

PRV start to discharge pressure 1.93 MPa (280.5 psig)

PRV capacity assumed large enough to maintain assumed pressure

tank material TC 128 steel

Based on the above tank:

- By AFFTAC, current thermal protection systems are more than adequate to protect a tank for 100 minutes from an engulfing fire with an effective radiating temperature of 816 °C.

- By AFFTAC, current thermal protection systems are more than adequate to protect a tank for 30 minutes from an torching fire with an effective radiating temperature of 1204 °C, and an effective torch emissivity of 0.536.
- AFFTAC simulations suggest that the pool fire test is the determining test. However, this conclusion changes if the torch properties are adjusted to more accurately represent a credible torch fire accident.
- By AFFTAC and TMID large defects can bring a tank to failure under engulfing fire conditions within 100 minutes.
- Because of uncertainties in the analysis it was concluded that a factor of safety (FOS) should be applied in this analysis. For the case of thermal protection, the FOS is defined as (tank burst pressure at 100 min in fire)/(tank pressure at 100 min in fire). The current thermal protection systems with no defects have  $FOS > 3.0$  at the 100 minute mark in the pool fire simulation. Based on various uncertainties (fire temperature, tank pressure, tank material properties) it was suggested that an  $FOS = 1.6$  would be reasonable.
- If a factor of safety of  $FOS = 1.6$  is used then a 112 tank with propane exposed to fire for 100 minutes can have between 4-24% defective insulation provided a steel jacket is present and is not in direct contact with the tank primary wall. The 24% end of the range assumes the remainder of the tank is protected with perfect insulation with properties as quoted for Kaowool ceramic blanket with 72 kg/m<sup>3</sup> density. The 4% end of the range assumes the remainder of the tank is protected with insulation with a conductance of 22.7 W/m<sup>2</sup>K which represents the maximum conductance that would pass the FRA plate test standard (i.e. keep steel plate sample temperature below 427° C for 100 minutes when exposed to a pool fire).
- The allowable defect area was strongly affected by input variables including:
  - assumed FOS
  - wall thickness
  - PRV setting
  - tank fill
  - fire temperature
  - commodity
  - tank surface emissivity
- Detailed analysis of defects suggested that:
  - as defect gets small the defect temperature may be reduced
  - for small defects, the normal stress may be reduced at high temperatures
  - several small, well separated defects are safer than one large defect

- Defects in the vapour space are more important than defects in the liquid space. However, the possibility of tank rollover makes this difficult to apply in the field.

The above conclusions have come from computer simulation results and therefore are not fully validated. Because of the extreme nature of this problem it is recommended that some testing be conducted to confirm these results.

## **7.2 Thermally Insulated Tanks**

For thermally insulated tanks the analysis is based only on the overall tank thermal conductance.

- Current non-defective thermal insulation systems just meet the required conductance as specified in CGSB standard. Therefore even very small defects may result in the tank not meeting the standards. This does not account for insulation discontinuities.
- If a defect is present then the external convective film coefficient affects the defect thermal conductance. Based on nominal convective coefficients and accounting for thermal radiation in the insulation annulus the allowable defect area is around 2%. This does not account for insulation discontinuities.
- some commodities such as chlorine cannot tolerate high temperatures (i.e. chlorine will cause steel to ignite at temperatures above 215 °C). Therefore some commodities cannot tolerate any insulation defects.

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**Appendix A: Standards for Thermal Protection and Thermal Insulation of Tank Cars**

## **§ 79.18 Thermal Protection Systems**

(a) Performance Standard. When this standard requires thermal protection on a tank car, it shall have sufficient thermal resistance so that there will be no release of any lading from within the tank car, except release through the pressure relief device, when subjected to:

(1) A pool fire for 100 min, and

(2) A torch fire for 30 min.

### **(b) Thermal Analysis**

(1) Compliance with the requirements of par. (a) of this section shall be verified by analyzing the fire effects on the entire surface of the tank. The analysis must consider the fire effects on and the heat flux through tank discontinuities, protective housings, underframes, metal jackets, insulation, and thermal protection. A complete record of each analysis shall be made, retained and, upon request, made available for inspection and copying by an authorized representative of Transport Canada. The procedures outlined in *Temperatures, Pressures and Liquid Levels of Tank Cars Engulfed in Fires*, DOT/FRA/OR&D-84/08.11, (1984) shall be deemed acceptable for analyzing the fire effects on the entire surface of the tank car.

(2) When the analysis shows that the thermal resistance of the tank car does not conform to par. (a) of this section, the thermal resistance of the tank car shall be increased by using a system listed by Transport Canada under par. (c) of this section or by testing a new and untried system and verifying it in accordance with Appendix D of this standard.

(c) Systems that No Longer Require Test Verification. Transport Canada maintains a list of thermal protection systems that comply with the requirements of Appendix D of this standard and that no longer require test verification. Information necessary to equip tank cars with one of these systems is available from the Director.

(d) Jacketed thermal protection systems shall be flashed around all openings so as to be weathertight. The exterior surface of a carbon steel tank and the inside surface of a carbon steel jacket shall be given a protective coating.

## **§ 79.100-4 Insulation**

(a) If insulation is applied, the tank shell and manway nozzle must be insulated with an approved material. The entire insulation must be covered with a metal jacket of a thickness not less than 11 gauge Manufacturers Standard Gauge (3.04 mm) (0.1196 in) and flashed

around all openings so as to be weathertight. The exterior surface of a carbon steel tank and the inside surface of a carbon steel jacket must be given a protective coating.

(b) If insulation is a specification requirement, it shall be of sufficient thickness so that the thermal conductance at 15.5°C (60°F) is not more than 1.533 kJ/h·m<sup>2</sup>·°C (0.075 Btu/h·ft<sup>2</sup>·°F) temperature differential. If exterior heaters are attached to the tank, the thickness of the insulation over each heater element may be reduced to one-half that required for the shell.

### § 79.101 Individual Specification Requirements Applicable to Pressure Tank Car Tanks

In addition to § 79.100, the individual specification requirements are as follows:

TC Specification	Individual Specification Requirements							
	Insulation	Bursting pressure, kPa (psi)	Minimum plate thickness, mm (in)	Test pressure, kPa (psi)	Minimum manway cover thickness, mm (in)	Bottom outlet	Bottom washout	Reference
105A100ALW	Yes	3448 (500)	15.9 (5/8)	690 (100)	63.5 (2½) <sup>2</sup>	No	No	—
105A200ALW	Yes	3448 (500)	15.9 (5/8)	1379 (200)	63.5 (2½) <sup>2</sup>	No	No	—
105A300ALW	Yes	5171 (750)	15.9 (5/8)	2069 (300)	66.7 (2½) <sup>2</sup>	No	No	—
105A100W	Yes	3448 (500)	14.3 (9/16) <sup>3</sup>	690 (100)	57.2 (2¼)	No	No	—
105A200W	Yes	3448 (500)	14.3 (9/16) <sup>3</sup>	1379 (200)	57.2 (2¼)	No	No	—
105A300W	Yes	5171 (750)	17.5 (11/16) <sup>1</sup>	2069 (300)	57.2 (2¼) <sup>7</sup>	No	No	—
0W	Yes	6895 (1000)	17.5 (11/16) <sup>1</sup>	2758 (400)	57.2 (2¼) <sup>7</sup>	No	No	—
105A500W	Yes	8619 (1250)	17.5 (11/16) <sup>1</sup>	3448 (500)	57.2 (2¼)	No	No	73.314(o)
105A600W	Yes	10342 (1500)	17.5 (11/16) <sup>1</sup>	4137 (600)	57.2 (2¼)	No	No	79.314(p),

TC Specification	Individual Specification Requirements							
	Insulation	Bursting pressure, kPa (psi)	Minimum plate thickness, mm (in)	Test pressure, kPa (psi)	Minimum manway cover thickness, mm (in)	Bottom outlet	Bottom washout	Reference
								73.314(g )
109A100AL W	Optional	3448 (500)	15.9 (5/8)	690 (100)	63.5 (2½) <sup>2</sup>	No	Optional	—
109A200AL W	Optional	3448 (500)	15.9 (5/8)	1379 (200)	63.5 (2½) <sup>2</sup>	No	Optional	—
109A300AL W	Optional	5171 (750)	15.9 (5/8)	2069 (300)	66.7 (2½) <sup>2</sup>	No	Optional	—
109A300W	Optional	3448 (500)	17.5 (11/16) <sup>1</sup>	2069 (300)	57.2 (2¼)	No	Optional	—
112A200W	Optional 4	3448 (500)	14.3 (9/16) <sup>3,5</sup>	1379 (200)	57.2 (2¼)	No	No	—
112A340W	Optional 4	5861 (850)	17.5 (11/16) <sup>1</sup>	2344 (340)	57.2 (2¼)	No	No	—
112A400W	Optional 4	6895 (1000)	17.5 (11/16) <sup>1</sup>	2758 (400)	57.2 (2¼)	No	No	—
112A500W	Optional 4	8619 (1250)	17.5 (11/16) <sup>1</sup>	3448 (500)	57.2 (2¼)	No	No	—
114A340W	Optional 4	5861 (850)	17.5 (11/16) <sup>1</sup>	2344 (340)	Note 6	Optional	Optional	103
114A400W	Optional 4	6895 (1000)	17.5 (11/16) <sup>1</sup>	2758 (400)	Note 6	Optional	Optional	103
120A200AL W	Yes	3448 (500)	15.9 5/8	1379 (200)	63.5 (2½) <sup>2</sup>	Optional	Optional	103
120A100W	Yes	3448 (500)	14.3 (9/16) <sup>3</sup>	690 (100)	57.2 (2¼)	Optional	Optional	103
120A200W	Yes	3448	14.3	1379	57.2	Optional	Optional	103

TC Specification n	Individual Specification Requirements							
	Insulation	Bursting pressure, kPa (psi)	Minimum plate thickness, mm (in)	Test pressure, kPa (psi)	Minimum manway cover thickness, mm (in)	Bottom outlet	Bottom washout	Reference
		(500)	(9/16) <sup>3</sup>	(200)	(2¼)	Optional	Optional	
120A300W	Yes	5171 (750)	17.5 (11/16) <sup>1</sup>	2069 (300)	57.2 (2¼)	Optional	Optional	103
120A400W	Yes	6895 (1000)	17.5 (11/16) <sup>1</sup>	2758 (400)	57.2 (2¼)	Optional	Optional	103
120A500W	Yes	8619 (1250)	17.5 (11/16) <sup>1</sup>	3448 (500)	57.2 (2¼)	Optional	Optional	103

**Notes to Pressure Tank Car Specifications**

1. When steel of 448 175 to 558 495 kPa (65 000 to 81 000 psi) minimum tensile strength is used, the thickness of the plates shall not be less than 16 mm (5/8 in) and when steel of 558 495 kPa (81 000 psi) minimum tensile strength is used, the minimum thickness of the plates shall not be less than 14 mm (9/16 in).
2. When approved material other than aluminum alloys are used, the thickness shall not be less than 57 mm (2¼ in).
3. When steel of 448 175 kPa (65 000 psi) minimum tensile strength is used, the minimum thicknesses of the plates shall not be less than 13 mm (½ in).
4. Tank cars not equipped with a thermal protection or an insulation system used for the transportation of a Class 2 (compressed gas) material shall have at least the upper two-thirds of the exterior of the tank, including manway nozzle and all appurtenances in contact with this area, finished with a coat of white paint.
5. For inside diameter of 2210 mm (87 in) or less, the thickness of the plates shall not be less than 13 mm (½ in).
6. See AAR Specifications for Tank Cars, Appendix E, E4.01 and § 79.103-2.
7. When the use of nickel is required by the lading, the thickness shall not be less than 50 mm (2 in).



**Appendix B: Procedures for Simulated Pool and Torch Fire Testing**

## PROCEDURES FOR SIMULATED POOL- AND TORCH-FIRE TESTING

- D1.** This test procedure is designed to measure the thermal effects of new or untried thermal protection systems and to test for system survivability when exposed to a 100 min pool fire and a 30 min torch fire.

### (a) Simulated Pool-fire Test

- (1) A pool-fire environment shall be simulated in the following manner:

(i) The source of the simulated pool fire shall be hydrocarbon fuel with a flame temperature of  $871 \pm 37.8^{\circ}\text{C}$  ( $1600 \pm 100^{\circ}\text{F}$ ), throughout the duration of the test.

(ii) A square bare plate with thermal properties equivalent to the material of construction of the tank car shall be used. The plate dimensions shall be not less than  $30.48 \times 30.48$  cm ( $1 \times 1$  ft) by nominal 1.6 cm (0.625 in) thick. The bare plate shall be instrumented with not less than nine thermocouples to record the thermal response of the bare plate. The thermocouples shall be attached to the surface not exposed to the simulated pool fire and shall be divided into nine equal squares with a thermocouple placed in the centre of each square.

(iii) The pool-fire simulator shall be constructed in a manner that results in total flame engulfment of the front surface of the bare plate. The apex of the flame shall be directed at the centre of the plate.

(iv) The bare plate holder shall be constructed so that the only heat transfer to the back side of the bare plate is by heat conduction through the plate and not by other heat paths.

(v) Before the bare plate is exposed to the simulated pool fire, none of the temperature recording devices may indicate a plate temperature in excess of  $37.8^{\circ}\text{C}$  ( $100^{\circ}\text{F}$ ) nor less than  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ).

(vi) A minimum of two thermocouple devices shall indicate  $427^{\circ}\text{C}$  ( $800^{\circ}\text{F}$ ) after  $13 \pm 1$  min of simulated pool-fire exposure.

(2) A thermal protection system shall be tested in the simulated pool-fire environment described in par. (a)(1) of this appendix in the following manner:

(i) The thermal protection system shall cover one side of a bare plate as described in par. (a)(1)(ii) of this appendix.

(ii) The non-protected side of the bare plate shall be instrumented with not less than nine thermocouples placed as described in par. (a)(1)(ii) of this appendix to record the thermal response of the plate.

(iii) Before exposure to the pool-fire simulation, none of the thermocouples on the thermal protection system configuration may indicate a plate temperature in excess of 37.8°C (100°F) nor less than 0°C (32°F).

(iv) The entire surface of the thermal protection system shall be exposed to the simulated pool fire.

(v) A pool-fire simulation test shall run for a minimum of 100 min. The thermal protection system shall retard the heat flow to the plate so that none of the thermocouples on the non-protected side of the plate indicate a plate temperature in excess of 427°C (800°F).

(vi) A minimum of three consecutive successful simulation fire tests shall be performed for each thermal protection system.

**(b) Simulated Torch-fire Test**

(1) A torch-fire environment shall be simulated in the following manner:

(i) The source of the simulated torch shall be a hydrocarbon fuel with a flame temperature of  $1204 \pm 37.8^\circ\text{C}$  ( $2200 \pm 100^\circ\text{F}$ ), throughout the duration of the test. Furthermore, torch velocities shall be  $64.4 \pm 16$  km/h ( $40 \pm 10$  mph) throughout the duration of the test.

(ii) A square bare plate with thermal properties equivalent to the material of construction of the tank car shall be used. The plate dimensions shall be at least  $121.92 \times 121.92$  cm ( $4 \times 4$  ft) by nominal 1.6 cm (0.625 in) thick. The bare plate shall be instrumented with not less than nine thermocouples to record the thermal response of the plate. The thermocouples shall be attached to the surface not exposed to the simulated torch and shall be divided into nine equal squares with a thermocouple placed in the centre of each square.

(iii) The bare plate holder shall be constructed so that the only heat transfer to the back side of the plate is by heat conduction through the plate and not by other heat paths. The apex of the flame shall be directed at the centre of the plate.

(iv) Before exposure to the simulated torch, none of the temperature recording devices may indicate a plate temperature in excess of 37.8°C (100°F) or less than 0°C (32°F).

(v) A minimum of two thermocouples shall indicate 427°C (800°F) in 4 min ± 30 s of torch-simulation exposure.

(2) A thermal protection system shall be tested in the simulated torch-fire environment described in par. (b)(1) of this appendix in the following manner:

(i) The thermal protection system shall cover one side of the bare plate identical to that used to simulate a torch fire under par. (b)(1)(ii) of this appendix.

(ii) The back of the bare plate shall be instrumented with not less than nine thermocouples placed as described in par. (b)(1)(ii) of this appendix to record the thermal response of the material.

(iii) Before exposure to the simulated torch, none of the thermocouples on the back side of the thermal protection system configuration may indicate a plate temperature in excess of 37.8°C (100°F) nor less than 0°C (32°F).

(iv) The entire outside surface of the thermal protection system shall be exposed to the simulated torch-fire environment.

(v) A torch-simulation test shall be run for a minimum of 30 min. The thermal protection system shall retard the heat flow to the plate so that none of the thermocouples on the backside of the bare plate indicate a plate temperature in excess of 427°C (800°F).

(vi) A minimum of two consecutive successful torch-simulation tests shall be performed for each thermal protection system.

## **Appendix C: TMID Listing**

program tank model with jacket

implicit real(a-z)  
character\*64 filename

common/failtime/ temp(100),sigult(100),sigyld(100),slope(100),  
&timerange(100),ndata  
common/wallstuff/wallthick,emm  
common/tankstuff/tankd,loverd,volume  
common/overhead/dtime  
common/lading/flading,tlading,pressure,mliq,mvap  
common/thermp/prop/tsat(100),psat(100),ug(100),uf(100),hg(100),  
& hf(100),vg(100),vf(100),sg(100),sf(100),propdata

common/ladprops/ts,ps,ugs,ufs,hgs,hfs,vgs,vfs,sgs,sfs  
common/prv/prvset,prvarea,cdg,cdf,mdot  
common/otherwall/otherwalltemp,xtjacket,kinsul,gap  
common/defect/deflength,thet atop,thet abot  
common/heat/qfirevapdef,qfireliqdef,qfirevapinsl,qfireliqinsl  
common/liquidwall/twliqdef,twliqinsl,tjliqdef,tjliqinsl  
common/areas/wallarea,liqarea,vaparea,vapdefectarea,liqdefectarea  
common/viewfactors/f11,f12,f13,f21,f22,f23,f31,f32,f33  
common/emmiss/emm1,emm2,emm3  
common/zoneareas/azone1,azone2,azone3  
common/zoneflux/q1,q2,q3  
common/firedata/fireh,fireemm,firefraction

common/insulationprops/ndens,ntemps,insultemp(100),  
& dens(100),insulk(100,100)  
common/ilenames/filename  
common/insulks/kinsljliq,kinsljvap,kinslwliq,kinslwvap  
common/ambient/tamb  
common/totalheatinput/qdottotal

OPEN(2,FILE='tank model with jacket.OUT',STATUS='old')

.... read in steel properties

open(3,file='AARTc128-550.dat',status='old')  
read(3,\*) ndata  
read(3,\*) (temp(i),sigult(i),sigyld(i),slope(i),  
&timerange(i),i=1,ndata)

.. filename for insulation properties

filename = "kaowool.dat"  
call readinsulprops

write(\*,\*) (temp(i),sigult(i),sigyld(i), slope(i),  
&timerange(i),i=1,ndata)

write(\*,\*) 'enter wall temperature (deg C)'  
read(\*,\*) walltemp

pi = 3.14159



```

write(*,*) 'data from file for batch runs ?? 1 = yes'
read(*,*) dataentry
if(dataentry.eq.1) then
C
C ... batch run from data file
C
  open(6,file='tmid.dat',status='old')
  read(6,*) ilad
  read(6,*) tankd,loverd,wallthick,emm
  write(*,*) tankd,loverd,wallthick,emm
  read(6,*) fos
  write(*,*) fos
  read(6,*) prvset
  write(*,*) prvset
  read(6,*) initfill,tinit
  write(*,*) initfill,tinit
  read(6,*) twallcrit
  write(*,*) twallcrit
  read(6,*) insultype,insuldens,conductance,gap
  write(*,*) insultype,insuldens,conductance,gap
  read(6,*) thetatop,thetabot,thetainc
  write(*,*) thetatop,thetabot,thetainc
  read(6,*) tfire,fireemm,fireh,firefraction
  write(*,*) tfire,fireemm,fireh,firefraction
C
  else
C
C ... single run from monitor
C
C
  write(*,*) 'enter lading type'
  write(*,*) ' '
  write(*,*) 'propane      = 1'
  write(*,*) 'ammonia      = 2'
  write(*,*) 'ethoxide     = 3'
  write(*,*) 'butane       = 4'
  write(*,*) 'propylene    = 5'
  write(*,*) 'isobutane    = 6'
  write(*,*) 'chlorine     = 7'
  write(*,*) 'isobutylene = 8'
  write(*,*) 'butadiene    = 9'
  read(*,*) ilad
C
  write(*,*) 'enter tank D (m)'
  read(*,*) tankd
  write(*,*) 'enter tank L/D '
  read(*,*) loverd
  write(*,*) 'enter fill fraction'
  read(*,*) initfill
C
  write(*,*) 'enter wall thickness (mm)'
  read(*,*) wallthick
  write(*,*) 'enter factor of safety FOS'
  read(*,*) fos
  write(*,*) 'enter prv operating pressure (MPa)'
  read(*,*) prvset
  write(*,*) 'enter surface emmissivity'
  read(*,*) emm
C
  write(*,*) 'enter insulation type '

```

```

write(*,*) ' 1 = kaowool '
write(*,*) ' 2 = constant conductance '
read(*,*) insultype
C
if(insultype.eq.1) write(*,*) 'enter kaowool density (kg/m^3) '
if(insultype.eq.1) read(*,*) insuldens
if(insultype.ne.1) write(*,*) 'enter insul conductance (W/m^2K) '
if(insultype.ne.1) read(*,*) conductance
C
write(*,*) 'enter jacket gap (mm)'
read(*,*) gap
write(*,*) 'enter initial lading temperature (deg C)'
read(*,*) tinit
write(*,*) 'enter critical wall temperature (deg C)'
read(*,*) twallcrit
C
write(*,*) 'enter insul defect length (m)'
C
read(*,*) deflength
C
write(*,*) 'enter angle to defect top (deg)'
read(*,*) thetatop
write(*,*) 'enter angle to defect bottom (deg)'
read(*,*) thetabot
C
C
write(*,*) 'enter fire temperature (deg C)'
read(*,*) tfire
write(*,*) 'enter fire emmissivity'
read(*,*) fireemm
write(*,*) 'enter fire convect coeff. (W/m^2K)'
read(*,*) fireh
write(*,*) 'enter fire exposure fraction'
read(*,*) firefraction
endif
C
C ... read in thermodynamic properties
C
C
if(ilad.eq.1) open(4,file='propane_si.dat',status='old')
if(ilad.eq.2) open(4,file='ammonia_si.dat',status='old')
if(ilad.eq.3) open(4,file='ethoxide_si.dat',status='old')
if(ilad.eq.4) open(4,file='butane_si.dat',status='old')
if(ilad.eq.5) open(4,file='propylen_si.dat',status='old')
if(ilad.eq.6) open(4,file='isobutane_si.dat',status='old')
if(ilad.eq.7) open(4,file='chlorine_si.dat',status='old')
if(ilad.eq.8) open(4,file='isobutylene_si.dat',status='old')
if(ilad.eq.9) open(4,file='butadiene_si.dat',status='old')
C
call properties
C
all emissivities = emm except liquid surface (0.9)
C
C
emm1 = emm
emm2 = emm
emm3 = 0.9
C
deflength = tankd*loverd
volume = pi*tankd**2/4.*tankd*loverd
C

```

```

write(2,*) ' '
write(2,*) ' Tank Model with Insulation Defects (TMID v1.0)'
write(2,*) ' _____'
write(2,*) ' '
c write(2,*) ' A. M. Birk May 1999'
c write(2,*) ' Department of Mechanical Engineering'
c write(2,*) ' Queen s University'
c write(2,*) ' birk@me.queensu.ca'
c write(2,*) ' '
c write(2,*) ' N O T E S '
c write(2,*) ' '
c write(2,*) ' this program has not been fully validated because of'
c write(2,*) ' a lack of data'
c write(2,*) ' '
c write(2,*) ' lading is propane'
c write(2,*) ' '
c write(2,*) ' insulation defect runs entire length of tank on one'
c write(2,*) ' side'
c write(2,*) ' '
write(2,*) ' input data'
write(2,*) ' _____'
write(2,*) ' '
if(ilad.eq.1) write(2,*) 'propane '
if(ilad.eq.2) write(2,*) 'ammonia '
if(ilad.eq.3) write(2,*) 'ethoxide '
if(ilad.eq.4) write(2,*) 'butane '
if(ilad.eq.5) write(2,*) 'propylene '
if(ilad.eq.6) write(2,*) 'isobutane '
if(ilad.eq.7) write(2,*) 'chlorine '
if(ilad.eq.8) write(2,*) 'isobutylene'
if(ilad.eq.9) write(2,*) 'butadiene '
c
write(2,*) 'fire temp (deg C) = ',tfire
write(2,*) 'fire emmissivity = ',fireemm
write(2,*) 'fire conv h (W/m^2K) = ',fireh
write(2,*) 'fire exposure frac = ',firefraction
c
write(2,*) 'tank D (m) = ',tankd
write(2,*) 'tank L/D = ',loverd
write(2,*) 'tank volume (m^3) = ',volume
write(2,*) 'tank initial fill fraction = ',initfill
write(2,*) 'wall thick (mm) = ',wallthick
write(2,*) 'PRV operating P (MPa) = ',prvset
c write(2,*) 'stress (MPa) = ',stress
write(2,*) 'surface emmissivity = ',emm
c write(2,*) 'view factor to lading = ',flading
write(2,*) 'lading initial temp(deg C) = ',tinit
if(dataentry.ne.1) write(2,*) 'critical wall temp (deg C) = ',
&twallcrit
c write(2,*) 'insulation k (W/mK) = ',kinsul
write(2,*) 'jacket gap (mm) = ',gap
write(2,*) 'insul defect length (m) = ',deflength
if(dataentry.ne.1)write(2,*) 'angle to defect top (deg) = ',
&thetatop
if(dataentry.ne.1)write(2,*) 'angle to defect bot (deg) = ',
&thetabot
c write(2,*) ' '
if(insultype.ne.1) then
write(2,*) 'constant insulation conductance (W/m^2 K)= ',
&conductance

```

```

else
write(2,*) 'temperature dependent insulation properties'
write(2,*) 'properties for KAOWOOL'
write(2,*) 'kaowool density (kg/m^3) = ',insuldens
endif
write(2,*) '_____ '
write(2,*) ' '

c
c
c do 1234 theta = 0,180,5
c thetatop = 45
c thetabot = 135
c call crossedstrings(theta)
c 1234 continue
c stop

c .... time step
c
c dtime = 1/60.
c tamb = tinit

c .... first calculate transient wall T's
c
c do 299 tfire = 800,900,10
c do 299 icond = 1,5
c conductance = 100.
c if(icond.eq.2) conductance = 50.
c if(icond.eq.3) conductance = 35
c if(icond.eq.4) conductance = 22.7
c if(icond.eq.5) conductance = 10
c
c
C+++++
+++
C+++++
+++
c
if(dataentry.eq.1) then
write(2,*) ' at failure (burst pressure)/(tank pressure) =',fos
write(2,*) '_____ '
write(2,*) ' '
write(2,*) ' '
write(2,*) ' defect defect fail P burst/ vapour temp
& tank lading'
write(2,*) ' top bot time press wall temp lading
& fill mass'
write(2,*) ' (deg) (deg) (min) (deg C) (deg C)
& (kg) '
write(2,*) ' '
else
endif

c
c ... loop for batch runs
c
savethetabot = thetabot
thetabot = thetatop - thetainc
1212 continue
thetabot = thetabot + thetainc
c do 299 thetabot = thetatop,savethetabot,thetainc
if(dataentry.ne.1) thetabot = savethetabot
write(*,*) ' defect at',thetatatop,' to ',thetabot

```

```

c
c ... initial conditions
c
    tloading = tinit
    fill = initfill
c
c ... vapour space temps
c
    walltemp = tamb
    otherwalltemp = tamb
    tjacket = tamb
    xtjacket = tamb
c
c... liquid space temps
c
    tjliqdef = tamb
    tjliqinsl = tamb
    twliqinsl = tamb
    twliqdef = tamb
c
c
c
c .... damage accumulators
c
    cummdamage = 0.0
    cummdamlm = 0.0
    birk2cumm = 0.0
    kfail = 1
c
c ... failure flags
c
    xlm = 0
    xrawdata = 0
    xaftec = 0
    xtcrit = 0
    xbirk2 = 0
c
c ... step through time
c
c    write(2,*) ' '
c    write(2,*) 'for fire T (deg C) = ',tfire
c
    if(dataentry.ne.1) then
        write(2,*) ' '
        write(2,2121)
        &'time press pbst fill tlad twvd twvi twli twld tjvd tjvi tjld tjli
        & mliq      mvap mtot mdot kins qdottot'
        write(2,2121)
        &'(min) (MPa) (MPa)      C      C      C      C      C      C      C      C
        & kg      kg      kg/s W/mK      kW      '
        write(2,2121)
        &'
        &_____
        &_____
2121 format(a103)
        write(2,*) ' '
        else
        endif
c
    counter = -1.
    steps = 1./dtype

```

```

C      do 298 time = 0.0,401.0,dtime
C
C      counter = counter + 1
C      write(*,*) 'entering fillangle',fill
C      call fillangle(fill,theta)
C      write(*,*) 'entering crossedstrings',fill
C      call crossedstrings(theta)
C      write(*,*) 'entering zones',fill
C      call zones(walltemp,otherwalltemp,tlading)
C      write(*,*) 'entering htinsul',fill
C      call htinsul(insultype,insuldens,conductance)
C      write(*,*) ' entering wallandjacket',fill
C      call wallandjacket(tfire,walltemp,tjacket,theta)
C      write(*,*) 'entering jacketfireheat',fill
C      call jacketfireheat(fill,theta,qdotttotal)
C      write(*,*) 'entering thermal',fill
C      write(*,*) time,qdotttotal,twliqdef,twliqinsl,tjliqdef,tjliqinsl
C      call thermal(qdotttotal,fill)
C
C
C
C
C      tankp = pressure
C      stress = (tankp)*tankd/2/wallthick*1000
C
C      if(counter.gt.steps) then
C      mtot = mliq+mvap
C      counter = 0.
C
C      if(dataentry.ne.1) write(2,22) time,pressure,pburst,fill,
C      & tlading,
C      & walltemp,otherwalltemp,twliqdef,twliqinsl,
C      & tjacket,xtjacket,tjliqdef,tjliqinsl,
C      & mliq,mvap,mtot,mdot,kinsul,qdotttotal/1000
C      else
C      endif
C
C 22  format(f5.1,2f5.1,f5.3,9f5.0,3f7.0,f5.1,f5.3,f6.0)
C
C      if(fill.lt.0.02) then
C      if(dataentry.ne.1) write(2,22) time,pressure,pburst,fill,
C      & tlading,
C      & walltemp,otherwalltemp,twliqdef,twliqinsl,
C      & tjacket,xtjacket,tjliqdef,tjliqinsl,
C      & mliq,mvap,mtot,mdot,kinsul,qdotttotal/1000
C      go to 297
C      else
C      endif
C
C
C
C ... failure time based on birk model
C
C      write(*,*) ' entering failuretime'
C      call failuretime(walltemp,stress,dtime,stressratio,yieldratio,
C      &damage,delay)
C
C.... failure time based on Larson Miller parameter
C

```



```

C      write(*,*) 'entering larsenmiller'
      call larsenmiller(stress,walltemp,ttflm)
C
C .... failure based on AFFTAC data
C
C      write(*,*) ' entering afftac'
      call aftac(stress,walltemp,aftacratio)
      pburst = pressure/aftacratio
C
C ... failure based on 2nd birk model
C
C      write(*,*) 'entering birk2'
      call birk2(stress,walltemp,birk2ratio,birk2damage)
C
C ... cummulative damage models
C
      cummdamage = cummdamage + damage
      cummdamlm = cummdamlm + dtime/ttflm
      birk2cumm = birk2cumm + birk2damage
C
C failure by critical wall temperature
C
      if(walltemp.ge.twallcrit.and.xtcrit.eq.0.0) then
      if(dataentry.ne.1) write(2,*) 'critical wall temperature reached'
C      write(2,20)time,walltemp,stressratio,yieldratio
      xtcrit = 1.
      else
      endif
C
C ... failure by ultimate stress
C
      if(aftacratio.ge.(1./fos).and.xaftec.eq.0.0) then
      if(dataentry.eq.1) then
      write(2,28)thetatop,thetabot,time,pburst/pressure,walltemp,
&tlading,fill,mtot
28      format( 2f7.1,2f9.2,2f10.1,f9.3,f9.1)
      go to 299
      else
C
      write(2,*) 'AFFTAC model with fos =',fos
      write(2,22) time,pressure,pburst,fill,tlading,
& walltemp,otherwalltemp,twliqdef,twliqinsl,
& tjacket,xtjacket,tjliqdef,tjliqinsl,
& mliq,mvap,mtot,mdot,kinsul,qdotttotal/1000
      xaftec = 1.
      endif
      else
      endif
C
C ... failure by LM parameter and cummulative damage
C
      if(dataentry.eq.1) go to 298
C
      if(cummdamlm.ge.kfail.and.xlm.eq.0.0) then
      write(2,*) 'Larson Miller model'
      write(2,20)time,walltemp,stressratio,yieldratio
      xlm = 1.
      else
      endif
C

```

```

c .... failure by cummulative damage and birk correlation
c
    if(cummdamage.ge.kfail.and.xrawdata.eq.0.0) then
    write(2,*) 'birk model'
    write(2,20)time,walltemp,stressratio,yieldratio
    xrawdata = 1.0
    else
    endif

c
c
c .... failure by cummulative damage and birk2 correlation
c
    if(birk2cumm.ge.kfail.and.xbirk2.eq.0.0) then
    write(2,*) 'birk 2nd model'
    write(2,20)time,walltemp,stressratio,yieldratio
    xbirk2 = 1.0
    else
    endif

c
c    test = xrawdata + xtcrit + xaftec + xlm
c    if(test.eq.4.) go to 200
c    write(4,20)tfire,time,tjacket,walltemp
20    format(3f9.1,f9.3,2f12.3,2f10.1)
c
100    continue
200    continue

c    write(2,20)tfire,time,walltemp,stressratio,yieldratio
c
300    continue

c
298    continue
297    continue
c
    if(dataentry.eq.1) then
    write(2,28)thetatop,thetabot,time,pburst/pressure,walltemp,
&tlading,fill,mtot
    else
    endif
299    continue

c
c ... loop until defect reaches tank bottom
c
    if(thetabot.lt.savethetabot) go to 1212
c
    stop
    end

c
c+++++
c
c
c
c
c+++++
c
    subroutine failuretime(walltemp,stress,dtime,
& stressratio,yieldratio,damage,delay)
c

```

```

        implicit real(a-z)
C
        common/failtime/ temp(100),sigult(100),sigyld(100),slope(100),
&timerange(100),ndata
C
        do 100 i=1,ndata-1
C
        if(walltemp.ge.temp(i).and.walltemp.le.temp(i+1)) then
        theslope =
& (slope(i+1)-slope(i))/(temp(i+1)-temp(i))*(walltemp-temp(i))
& + slope(i)
        thesigult =
& (sigult(i+1)-sigult(i))/(temp(i+1)-temp(i))*(walltemp-temp(i))
& + sigult(i)
        thesigyld =
& (sigyld(i+1)-sigyld(i))/(temp(i+1)-temp(i))*(walltemp-temp(i))
& + sigyld(i)
        thetimerange =
& (timerange(i+1)-timerange(i))/(temp(i+1)-temp(i))*
& (walltemp-temp(i)) + timerange(i)
C
        go to 200
        else
        endif
100 continue
200 continue
C
        stressratio = stress/thesigult
        yieldratio = stress/thesigyld
        failtime = theslope*(1-stressratio)
        if(yieldratio.lt.1.0) failtime = 99999.
        if(failtime.lt.0.0) failtime = 0.0
        delay = thetimerange
C
        if(failtime.eq.0.0) failtime = 0.0001
        damage = dtime/failtime
C
        cummdamage = cummdamage + damage
C
C
C
        write(2,*) walltemp,stressratio,yieldratio,failtime,delay
C
300 continue
C
        return
        end
C
C+++++
C
C
C
C+++++
C
        subroutine wallandjacket(tfire,walltemp,tjacket,theta)
C
        implicit real(a-z)
C
        common/wallstuff/wallthick,emm
        common/overhead/dtime
        common/lading/flading,tlading,pressure,mliq,mvap
        common/otherwall/otherwalltemp,xtjacket,kinsul,gap
        common/liquidwall/twliqdef,twliqinsl,tjliqdef,tjliqinsl

```

```

common/heat/qfirevapdef,qfireliqdef,qfirevapinsl,qfireliqinsl
common/areas/wallarea,liqarea,vaparea,vapdefectarea,liqdefectarea
common/viewfactors/f11,f12,f13,f21,f22,f23,f31,f32,f33
common/defect/deflength,thetatop,thetabot
common/zoneflux/q1,q2,q3
common/firedata/fireh,fireemm,firefraction
common/insulks/kinsljliq,kinsljvap,kinslwliq,kinslwvap
common/tankstuff/tankd,loverd,volume
common/ambient/tamb

```

```

sig = 5.67e-8
pi = 3.14159

```

```

hliq = 5000.0
hvap = 0.0

```

```

... 2phase stuff

```

```

h2phase = 200
frothheight = 0.1
thetafroth =
&arcsin((tankd/2*sin(theta*pi/180) + frothheight)/tankd/0.5)

```

```

rhosteel = 7800.
csteel = 447.

```

```

wjacket = 3./1000.
kair = 0.06
hgap = 1.00

```

```

kinsul = 0.1

```

```

... insulation properties

```

```

kinslliq = 0.5*(kinslwliq+kinsljliq)
kinslvap = 0.5*(kinslwvap+kinsljvap)

```

```

V A P O U R   S P A C E

```

```

calculate new jacket temperature in defect area

```

```

qfire = fireemm*emm*sig*((tfire+273)**4-(tjacket+273)**4)
& + fireh*(tfire-tjacket)

```

```

qfront = (1-fireemm)*emm*sig*((tjacket+273)**4-(tamb+273)**4)

```

```

qgradback = emm/(2-emm)*sig*((tjacket+273)**4-(walltemp+273)**4)
qbackconv = hgap*(tjacket-walltemp)

```

```

tnewjacket = tjacket +
& 60.*dtime/rhosteel/wjacket/csteel*
& (qfire - qfront - qgradback - qbackconv)

```

```

tjacket = tnewjacket
if(theta.lt.thetatop) tjacket = tjliqdef

```

```

now calculate new wall temperature in defect

```

```

C
C
qjacket = emm/(2-emm)*sig*((tjacket+273)**4-(walltemp+273)**4)
qcond = hgap*(tjacket-walltemp)
C
C
qbackside = emm*sig*f13*((walltemp+273)**4-(tlading+273)**4)
& + emm*sig*f12*((walltemp+273)**4-(otherwalltemp+273)**4)
C
qbackside = q1
C
hback = hvap
if(theta.eq.0.0) hback = hliq
C
if(theta.lt.thetafroth) hback = h2phase
if(theta.lt.thetatop) hback = hliq
C
qconv = hback*(walltemp-tlading)
C
dtemp = (qjacket + qcond - qconv - qbackside)*dtime*60
& /rhosteel/csteel/(wallthick/1000)
walltemp = walltemp + dtemp
C
if(vapdefectarea.eq.0.0) walltemp = otherwalltemp
C
if(theta.lt.thetatop) walltemp = twliqdef
C
if(theta.eq.0.0) walltemp = twliqdef
C
C
qfirevapdef = qbackside + qconv
C
C
now consider jacket in insulated part of vapour space wall
C
xqfire = fireemm*emm*sig*((tfire+273)**4 - (xtjacket+273)**4)
& + fireh*(tfire-xtjacket)
C
qfront = (1-fireemm)*emm*sig*((xtjacket+273)**4-(tamb+273)**4)
xqback = (kinslvap/(gap/1000.))*(xtjacket - otherwalltemp)
C
xtnewjacket = xtjacket +
& 60.*dtime/rhosteel/wjacket/csteel*
& (xqfire - qfront - xqback)
C
xtjacket = xtnewjacket
C
if(vapdefectarea.eq.0.0) tjacket = tjliqdef
C
... insulated wall in vapour space
C
xqcond = kinslvap/(gap/1000.)*(xtjacket-otherwalltemp)
C
xqbackside = emm*sig*f23*((otherwalltemp+273)**4
& - (tlading+273)**4)
& + emm*sig*f21*((otherwalltemp+273)**4. - (walltemp+273)**4.)
C
xqbackside = q2
C
hback = hvap
C
if(theta.lt.thetafroth) hback = h2phase
if(theta.eq.0.0) hback = hliq
xqconv = hback*(otherwalltemp-tlading)
C
xdtemp = (xqcond - xqconv - xqbackside)*dtime*60

```

```

& /rhosteel/csteel/(wallthick/1000)
C
otherwalltemp = otherwalltemp + xdtemp
C
if(theta.eq.0.0) otherwalltemp = twliqinsl
C
if(vaparea.eq.0.0) otherwalltemp = twliqinsl
C
qfirevapinsl = xqbackside + xqconv
C
C+++++
C
C ... L I Q U I D   W A L L
C
C ... jacket T in defect liq area
C
qfireliqdef = fireemm*emm*sig*((tfire+273)**4-(tjliqdef+273)**4)
& + fireh*(tfire-tjliqdef)
C
qfront = (1-fireemm)*emm*sig*((tjliqdef+273)**4-(tamb+273)**4)
gradbackliqdef =
& emm/(2-emm)*sig*((tjliqdef+273)**4-(twliqdef+273)**4)
qbackconvliqdef = hgap*(tjliqdef-twliqdef)
C
tnewjliqdef = tjliqdef +
& 60.*dtime/rhosteel/wjacket/csteel*
& (qfireliqdef - qfront - gradbackliqdef - qbackconvliqdef)
C
tjliqdef = tnewjliqdef
C
C ... jacket T in insulated liq area
C
qfireliqinsl = fireemm*emm*sig*((tfire+273)**4-(tjliqinsl+273)**4)
& + fireh*(tfire-tjliqinsl)
qfront = (1-fireemm)*emm*sig*((tjliqinsl+273)**4-(tamb+273)**4)
qbackliqinsl = (kinslliq/(gap/1000.))*(tjliqinsl - twliqinsl)
C
tnewjliqinsl = tjliqinsl +
& 60.*dtime/rhosteel/wjacket/csteel*
& (qfireliqinsl - qfront - qbackliqinsl)
C
tjliqinsl = tnewjliqinsl
C
if(liqdefectarea.eq.0.0) tjliqdef = tjliqinsl
C
C
C now calculate new liq wall temperature in defect
C
qjackliqdef =
& emm/(2-emm)*sig*((tjliqdef+273)**4-(twliqdef+273)**4)
qconvliqdef = hgap*(tjliqdef-twliqdef)
C
qbackliqdef = hliq*(twliqdef-tlading)
C
dtemp = (qjackliqdef + qconvliqdef - qbackliqdef)*dtime*60
& /rhosteel/csteel/(wallthick/1000)
C
twliqdef = twliqdef + dtemp
if(theta.gt.thetabot) twliqdef = twliqinsl
C
qfireliqdef = qbackliqdef
C
C

```



```

c... insulated wall in liquid space
c
      xqcondliq = kinslliq/(gap/1000.)*(tjliqinsl-twliqinsl)
c
      xqconvliq = hliq*(twliqinsl-tlading)
c
      xdtempliq = (xqcondliq - xqconvliq)*dtime*60
& /rhosteel/csteel/(wallthick/1000)
      twliqinsl = twliqinsl + xdtempliq
c
      if(liqdefectarea.eq.0.0) twliqdef = twliqinsl
c
      qfireliqinsl = xqconvliq
c
c
      return
      end
c
c+++++
c
c
c
c+++++
c
      subroutine wallt(tfire,walltemp)
c
      implicit real(a-z)
c
      common/wallstuff/wallthick,emm
      common/overhead/dtime
      common/lading/flading,tlading,pressure,mliq,mvap
c
      sig = 5.67e-8
      hbackside = 5.
      rhosteel = 7800.
      csteel = 447.
c
      calculate new wall temperature
c
c
      qfire = emm*sig*((tfire+273)**4-(walltemp+273)**4)
      qbackconv = hbackside*(walltemp-tlading)
c
      qbackside = emm*sig*flading*((walltemp+273)**4-(tlading+273)**4)
c
      dtemp = (qfire - qbackconv - qbackside)*dtime*60.
& /rhosteel/csteel/(wallthick/1000.)
      walltemp = walltemp + dtemp
c
      return
      end
c
c+++++
c
c
c+++++
c
      subroutine laronmiller(stress,walltemp,ttflm)
c
c

```

```
implicit real(a-z)
```

```
ult = 550.
```

```
plm = 17000 - 15.6*stress
```

```
if(stress.gt.530.) plm = 8750 - 435.*(stress - 530.)
```

```
if(stress.gt.ult) plm = 0.0
```

```
ratio = plm/walltemp
```

```
if(ratio.lt.17.) ttflm = 0.001
```

```
if(ratio.gt.30.) ttflm = 99999.
```

```
if(ratio.ge.17.and.ratio.le.30.) ttflm = 10.**(ratio-20.)
```

```
return
```

```
end
```

```
subroutine aftac(stress,walltemp,aftacratio)
```

```
implicit real(a-z)
```

```
ult = 550.
```

```
ttnv = (walltemp*9./5.+32.+460.)/1000.
```

```
if(ttnv.lt.1.260) fctr = 1.0 - (.54)*(ttnv-.46)**4.
```

```
if(ttnv.ge.1.260) fctr = 1.74 - 1.17*(ttnv-.46)
```

```
ulthot = fctr*ult
```

```
aftacratio = stress/ulthot
```

```
return
```

```
end
```

```
subroutine birk2(stress,walltemp,birk2ratio,birk2damage)
```

```
implicit real(a-z)
```

```
common/overhead/dtime
```

```
ult = 550.
```

```
ttnv = (walltemp*9./5.+32.+460.)/1000.
```

```
if(ttnv.lt.1.260) fctr = 1.0 - (.54)*(ttnv-.46)**4.
```

```
if(ttnv.ge.1.260) fctr = 1.74 - 1.17*(ttnv-.46)
```

```
if(fctr.lt.0.01) fctr = 0.01
```

```
kfactor = 0.055
```

```
ulthot = fctr*ult
```

```
birk2ratio = stress/ulthot
```

```
if(birk2ratio.ge.1.0) then
```

```

        failtime = .0001
        else
        failtime = 10.**((1.0-birk2ratio)/kfactor)
        endif
C
        birk2damage = dtime/failtime
C
        return
        end
C
C
C+++++
C
C
C+++++
C
        subroutine fillangle(fill,theta)
C
        implicit real(a-z)
        common/lading/flading,tlading,pressure,mliq,mvap
C
        if(fill.gt.0.998) then
        theta = 0.0
        flading = 1.
        else
C
        theta = 0.0
        dtheta = 5.
        pi = 3.14159
        counter = 0.
C
100 continue
        counter = counter + 1.
        if(counter.gt.100) then
        stop 'fillangle not converging'
        else
        endif
C
        tryfill = (((360. - 2.*theta)/360.)*pi/4
& + 1./4.*sin(theta/180.*pi)*cos(theta/180.*pi))/(pi/4.)
C
        error = (tryfill - fill)/fill
C
        write(*,*) theta,tryfill,fill,error
C
        if(error.gt.0.002) then
        theta = theta + dtheta
        go to 100
        else
        endif
        if(error.lt.0.0) then
        theta = theta - dtheta
        dtheta = dtheta/5.
        theta = theta + dtheta
        go to 100
        else
        endif
C
200 continue
C

```

```

c .... view factor to liquid
c
c   flading = sin(theta*pi/180.)/pi/(2*theta/360.)
c
c   endif
c   return
c   end
c
c+++++
c
c
c
c
c+++++
c
c   subroutine jacketfireheat(fill,theta,qdottotal)
c
c   implicit real(a-z)
c
c   common/wallstuff/wallthick,emm
c   common/overhead/dtime
c   common/tankstuff/tankd,loverd,volume
c   common/lading/flading,tlading,pressure,mliq,mvap
c   common/otherwall/otherwalltemp,xtjacket,kinsul,gap
c   common/defect/deflength,thetabot,thetabot
c   common/heat/qfirevapdef,qfireliqdef,qfirevapinsl,qfireliqinsl
c   common/areas/wallarea,liqarea,vaparea,vapdefectarea,liqdefectarea
c   common/zoneflux/q1,q2,q3
c   common/zoneareas/azone1,azone2,azone3
c   common/firedata/fireh,fireemm,firefraction
c
c   pi = 3.14159
c
c.... figure out all the areas
c
c
c   wallarea = 2*pi*tankd**2/4 + pi*tankd**2*loverd
c
c   if(theta.le.thetabot.and.theta.ge.thetabot) then
c     vapdefectarea = deflength*pi*tankd*(theta-thetabot)/360
c     liqdefectarea = deflength*pi*tankd*(thetabot-theta)/360
c   else
c     endif
c
c   if(theta.lt.thetabot) then
c     vapdefectarea = 0.0
c     liqdefectarea = deflength*pi*tankd*(thetabot-thetabot)/360
c   else
c     endif
c
c   if(theta.gt.thetabot) then
c     vapdefectarea = deflength*pi*tankd*(thetabot-thetabot)/360
c     liqdefectarea = 0.0
c   else
c     endif
c
c   vaparea = 2.*theta/360.*pi*tankd**2*loverd
c   & + 2*(1. - fill)*pi*tankd**2/4 - vapdefectarea
c
c   liqarea = wallarea - vaparea - vapdefectarea - liqdefectarea

```

```

C
C ... total heat transfer rate to lading
C
C
C   write(*,99) qfirevapinsl/1000,qfirevapdef/1000,
C   &qfireliqinsl/1000,qfireliqdef/1000,qdottotal/1000
C   write(*,99) vaparea,vapdefectarea,liqarea,liqdefectarea,wallarea
C 99 format(6f10.2)
C
C   qdottotal = (vaparea*qfirevapinsl
C   &           + qfireliqinsl*liqarea
C   &           + qfirevapdef*vapdefectarea
C   &           + qfireliqdef*liqdefectarea)
C
C   qdottotal = firefraction*(- azone3*q3
C   &           + qfireliqinsl*liqarea
C   &           + qfireliqdef*liqdefectarea)
C
C   write(*,10) qfirevapdef*vapdefectarea,vaparea*qfirevapinsl
C 10 format(2x,2f10.2)
C
C   return
C   end
C
C+++++
C
C
C
C+++++
C
C   subroutine thermal(qdottotal,fill)
C
C   implicit real(a-z)
C
C   common/wallstuff/wallthick,emm
C   common/overhead/dtime
C   common/tankstuff/tankd,loverd,volume
C   common/lading/flading,tlading,pressure,mliq,mvap
C   common/thermprop/tsat(100),psat(100),ug(100),uf(100),hg(100),
C   & hf(100),vg(100),vf(100),sg(100),sf(100),propdata
C   common/ladprops/ts,ps,ugs,ufs,hgs,hfs,vgs,vfs,sgs,sfs
C   common/prv/prvset,prvarea,cdg,cdf,mdot
C
C ... determine masses, etc based on fill level and lading temperature
C
C   call tables(tlading)
C   pressure = ps/1000. - 0.101
C   volvap = (1.-fill)*volume
C   volliq = fill*volume
C   mvap = volvap/vgs
C   mliq = volliq/vfs
C   mtot = mliq+mvap
C   mdot = 0.0
C
C   write(*,*) fill,volume,volvap,volliq,mvap,mliq
C
C .... energy balance if PRV is closed ++++++
C

```

```

c      if(pressure.ge.prvset) go to 300
      if(fill.eq.1.0) go to 310
c
      u1 = mvap*ugs + mliq*ufs
      u2 = u1 + (qdottotal/1000.)*dtime*60.
      change = u2-u1
c      write(*,*) ps,fill,mliq,mvap,u2,u1,change
      v2 = volume
c
      dt = 0.01
      tladnew = tlading - dt
      counter = 0
c
c ... iterate for new state
c
c 100 continue
      counter = counter + 1
      if(counter.gt.100) stop 'thermal not converging'
      tladnew = tladnew + dt
      call tables(tladnew)
c
      mvap2 = (u2 - mtot*ufs)/(ugs - ufs)
c      if(mvap2.lt.0.0) mvap2 = 0.0
      mliq2 = mtot - mvap2
c
      vol2 = mvap2*vgs + mliq2*vfs
      error = (volume - vol2)/volume
c
c      write(*,10) qdottotal,tladnew,mvap,mliq,mvap2,mliq2,ps,error
c 10  format(8f9.2)
c
      if(abs(error).lt.0.0001) go to 200
      if(error.gt.0.0) then
        tladnew = tladnew - dt
        dt = dt/5.
        go to 100
      else
        go to 100
      endif
c
c 200 continue
      go to 400
c 300 continue
c
c ... energy balance if PRV is open ++++++
++
c
c      write(*,*) 'entering thermal with fill = 1.0 and prv open'
      tladnew = tlading
      call tables(tladnew)
c
      mdot = qdottotal/1000./(hgs-hfs)
      mliq2 = mliq - mdot*dtime*60.
      vliq2 = mliq2*vfs
      vvap2 = volume - vliq2
      mvap2 = vvap2/vgs
c      write(*,*) tlading,mdot,mliq,mliq2,mvap2
      go to 400
c

```



```

310 continue
c
c+++++
c
c
c .... liquid full with p < p prv
c
    u1 = mvap*ugs + mliq*ufs
    u2 = u1 + (qdottotal/1000.)*dtime*60.
    change = u2-u1
c    write(*,*) u2,u1,change
    v2 = volume
c
    dt = 0.02
    tladnew = tladng - dt
    counter = 0
c
c ... iterate for new state
c
110 continue
    counter = counter + 1
    if(counter.gt.30) stop 'thermal not converging -- liquid full'
    tladnew = tladnew + dt
    call tables(tladnew)
c
    mvap2 = 0.0
    mliq2 = mtot - mvap2
    u2try = mliq2*ufs
c
    error = (u2 - u2try)/u2
c
c    write(*,10) qdottotal,tladnew,mvap,mliq,mvap2,mliq2,ps,error
c 10    format(8f9.2)
c
    if(abs(error).lt.0.000003) go to 210
    if(error.lt.0.0) then
        tladnew = tladnew - dt
        dt = dt/5.
        go to 110
    else
        go to 110
    endif
c
210 continue
    fill = mliq2*vfs/volume
    overfill = fill - 1.
    if(overfill.gt.0.0) then
        fill = 1.
        mliq2 = volume/vfs
        mdot = overfill*volume/vfs/(dtime*60.)
    else
        endif
    go to 400
c
400 continue
c
    tladng = tladnew
    pressure = ps/1000. - 0.101
    fill = mliq2*vfs/volume
    if(fill.gt.0.999.and.pressure.lt.prvset) fill = 1.0

```

```

C      if(fill.gt.0.995) stop 'tank liquid full'
C
C      write(*,*) tlading,pressure,fill,mdot
C
C      return
C      end
C
C
C+++++
C
C
C
C+++++
C
C      subroutine newthermal(qdottotal,fill)
C
C      implicit real(a-z)
C
C      common/wallstuff/wallthick,emm
C      common/overhead/dtime
C      common/tankstuff/tankd,loverd,volume
C      common/lading/flading,tlading,pressure,mliq,mvap
C      common/thermprop/tsat(100),psat(100),ug(100),uf(100),hg(100),
C      & hf(100),vg(100),vf(100),sg(100),sf(100),propdata
C      common/ladprops/ts,ps,ugs,ufs,hgs,hfs,vgs,vfs,sgs,sfs
C      common/prv/prvset,prvarea,cdg,cdf,mdot
C
C      ... determine masses, etc based on fill level and lading temperature
C
C      call tables(tlading)
C      pressure = ps/1000. - 0.101
C      volvap = (1.-fill)*volume
C      volliq = fill*volume
C      mvap = volvap/vgs
C      mliq = volliq/vfs
C      mtot = mliq+mvap
C      mdot = 0.0
C
C      write(*,*) fill,volume,volvap,volliq,mvap,mliq
C
C      ... energy balance if PRV is closed ++++++
C
C      if(pressure.ge.prvset) go to 300
C      if(fill.eq.1.0) go to 310
C
C      u1 = mvap*ugs + mliq*ufs
C      u2 = u1 + (qdottotal/1000.)*dtime*60.
C      change = u2-u1
C      call tables(tlading + 0.2)
C      u2try = mvap*ugs + mliq*ufs
C      cv = (u2try - u1)/0.2
C      tempchange = (u2-u1)/cv
C      write(*,*) ps,fill,mliq,mvap,u2,u1,change
C      v2 = volume
C
C      tladnew = tlading + tempchange
C      call tables(tladnew)

```

```

      mvap2 = (u2 - mtot*ufs)/(ugs - ufs)
      mliq2 = mtot - mvap2
c
      vol2 = mvap2*vgs + mliq2*vfs
      error = (volume - vol2)/volume
c
      write(*,10) qdottotal,tladnew,mvap,mliq,mvap2,mliq2,ps,error
10    format(8f9.2)
c
200  continue
      go to 400
300  continue
c
c ... energy balance if PRV is open ++++++
++
c
c      write(*,*) 'entering thermal with fill = 1.0 and prv open'
      tladnew = tlading
      call tables(tladnew)
c
      mdot = qdottotal/1000./(hgs-hfs)
      mliq2 = mliq - mdot*dtime*60.
      vliq2 = mliq2*vfs
      vvap2 = volume - vliq2
      mvap2 = vvap2/vgs
c      write(*,*) tlading,mdot,mliq,mliq2,mvap2
      go to 400
c
310  continue
c
c+++++
c
c
c .... liquid full with p < p prv
c
      u1 = mvap*ugs + mliq*ufs
      u2 = u1 + (qdottotal/1000.)*dtime*60.
      change = u2-u1
c      write(*,*) u2,u1,change
      v2 = volume
c
      dt = 0.02
      tladnew = tlading - dt
      counter = 0
c
c ... iterate for new state
c
110  continue
      counter = counter + 1
      if(counter.gt.30) stop 'thermal not converging -- liquid full'
      tladnew = tladnew + dt
      call tables(tladnew)
c
      mvap2 = 0.0
      mliq2 = mtot - mvap2
      u2try = mliq2*ufs
c
      error = (u2 - u2try)/u2
c
c      write(*,10) qdottotal,tladnew,mvap,mliq,mvap2,mliq2,ps,error

```





```

C      implicit real(a-z)
C
C      character*64 filename
C
C      common/otherwall/otherwalltemp,xtjacket,kinsul,gap
C      common/heat/qfirevapdef,qfireliqdef,qfirevapinsl,qfireliqinsl
C      common/liquidwall/twliqdef,twliqinsl,tjliqdef,tjliqinsl
C
C      common/insulationprops/ndens,ntemps,insultemp(100),
C      & dens(100),insulk(100,100)
C      common/filenames/filename
C      common/insulks/kinsljliq,kinsljvap,kinslwliq,kinslwvap
C
C      .... for CFR 179 the highest conductance is 4 Btu/hr ft^2 F
C      =
C
C      for 0.5 inch insulation this gives a k = 0.167 Btu/hr ft F
C      = 0.289 W/m K
C
C      asbestos 30 lb/ft^3      k = 0.097 Btu/hr ft F
C      = 0.17 W/m K
C
C
C      nomkinsul = 0.2
C      tnom = 20
C      hotkinsul = 0.4
C      thot = 900
C
C      kinsul = nomkinsul
C      & + (xtjacket-tnom)/(thot-tnom)*(hotkinsul-nomkinsul)
C
C      ... from AFFTAC
C
C      tt = (xtjacket*9/5 + 32)/1000.
C      cknd = 0.2 + 0.1938*tt + 0.6769*tt**2
C      kbrit = cknd/12.
C
C      kinsul = kbrit/.5778
C
C      conductance = 22.7
C
C
C      ... insultype = 1 is kaowool
C
C      if(insultype.eq.1) then
C      tinsuljliq = tjliqinsl
C      tinsuljvap = xtjacket
C      tinsulwliq = twliqinsl
C      tinsulwvap = otherwalltemp
C
C      call insulprops(tinsuljliq,insuldens,kinsljliq)
C      call insulprops(tinsulwliq,insuldens,kinslwliq)
C      call insulprops(tinsuljvap,insuldens,kinsljvap)
C      call insulprops(tinsulwvap,insuldens,kinslwvap)
C      kinsul = .25*(kinslwliq+kinslwvap+kinsljliq+kinsljvap)
C
C      else
C      kinsul = conductance * gap/1000
C      kinsljliq = kinsul

```



```

      kinslwliq = kinsul
      kinsljvap = kinsul
      kinslwvap = kinsul
    endif

C
      return
    end

C
C+++++
C
C
C
C+++++
C
      subroutine crossedstrings(theta)
C
      implicit real(a-z)
C
      common/defect/deflength,thetatop,thetabot
      common/heat/qfirevapdef,qfireliqdef,qfirevapinsl,qfireliqinsl
      common/areas/wallarea,liqarea,vaparea,vapdefectarea,liqdefectarea
      common/tankstuff/tankd,loverd,volume
      common/viewfactors/f11,f12,f13,f21,f22,f23,f31,f32,f33
      common/zoneareas/azone1,azone2,azone3
C
C      1 = vapour wall defect
C      2 = vapour wall insulated
C      3 = liquid surface
C
C
      pi = 3.14159
      rtank = tankd/2.
      tanklength = tankd*loverd
      if(theta.le.thetabot.and.theta.gt.thetatop) go to 100
      if(theta.gt.thetabot) go to 200
      if(theta.le.thetatop) go to 300
C
C      ... case 1 -- liquid level above bottom of defect
C                  defect spans from thetatop to theta
C
C
100  continue
      cb = 2*rtank*sin(theta/180*pi)
      ab = 2*rtank*sin((theta-thetatop)/2./180.*pi)
      ac = sqrt(2.*rtank**2.-2.*rtank**2.*cos((theta+thetatop)/180*pi))
      aliqsurf = cb
      arcdefect = (theta - thetatop)/360.*pi*tankd
      arcinsl = 2.*theta/360.*pi*tankd - arcdefect
C
      f13a1 = (ab + cb - ac)/2.
      f12a1 = (ab + ac - cb)/2.
      if(arcdefect.le.0.0) then
      f13 = 1.0
      f12 = 0.0
      else
      f13 = f13a1/arcdefect
      f12 = f12a1/arcdefect
      endif
      f11 = 1 - f12 - f13
C

```

```

f23a2 = (ac + cb - ab)/2.
f21a2 = (ac + ab - cb)/2.
if(arcins1.le.0.0) then
f21 = 0.0
f23 = 1.0
else
f21 = f21a2/arcins1
f23 = f23a2/arcins1
endif
f22 = 1 - f21 - f23
goto 400
c
200 continue
c
c ... case 2 -- liquid level is below thetabot
c          defect spans from thetatop to thetabot
c
c
cd = 2.*rtank*sin(theta/180*pi)
dc = cd
ab = 2.*rtank*sin((thetabot-thetatop)/2./180.*pi)
ba = ab
bd = 2.*rtank*sin((theta-thetabot)/2./180.*pi)
db = bd
ac = sqrt(2.*rtank**2.-2.*rtank**2.*cos((theta+thetatop)/180*pi))
ca = ac
bc = sqrt(2.*rtank**2.-2.*rtank**2.*cos((theta+thetabot)/180*pi))
cb = bc
ad = 2*rtank*sin((theta-thetatop)/2./180.*pi)
da = ad
c
aliqsurf = cd
arcdefect = (thetabot - thetatop)/360.*pi*tankd
arcins1 = 2.*theta/360.*pi*tankd - arcdefect
c
c
f13a1 = (ad + bc - ac - bd)/2.
f12a1 = (ab + ac - bc)/2. + (ab + bd - ad)/2.
if(arcdefect.le.0.0) then
f13 = 1.0
f12 = 0.0
else
f13 = f13a1/arcdefect
f12 = f12a1/arcdefect
endif
f11 = 1 - f12 - f13
c
f21a2 = (ac + ab - bc)/2. + (ab + bd - ad)/2.
f23a2 = (ac + cd - ad)/2. + (bd + cd - bc)/2.
if(arcins1.le.0.0) then
f21 = 0.0
f23 = 1.0
else
f21 = f21a2/arcins1
f23 = f23a2/arcins1
endif
f22 = 1 - f21 - f23
go to 400
c
c .... case 3 -- defect is below liquid level

```

```

C
C
C
300 continue
    f11 = 0.
    f12 = 0.
    f13 = 0.
C
    f21 = 0.
    cd = 2.*rtank*sin(theta/180*pi)
    aliqsurf = cd
    f23a2 = aliqsurf
    arcdefect = 0.0
    arcinsl = 2.*theta/360.*pi*tankd - arcdefect
    if(arcinsl.eq.0.0) then
        f23 = 1.0
    else
        f23 = f23a2/arcinsl
    endif
    f22 = 1. - f23 - f21
C
400 continue
    if(aliqsurf.gt.0.0) then
        f31 = f13/aliqsurf*arcdefect
        f32 = f23/aliqsurf*arcinsl
        f33 = 0.0
    else
        f31 = 0.
        f32 = 0.
        f33 = 0.
    endif
    azonel = vapdefectarea
    azone2 = vaparea
    azone3 = aliqsurf*tanklength
C
C    write(2,10) theta,thetabot,thetabot,f11,f12,f13,f21,f22,f23,
C    & f31,f32,f33
C 10 format(2x,3f6.0,9f5.3)
C
    return
end
C
C
C
C
C
C
C
subroutine zones(t1,t2,t3)
C
    implicit real(a-z)
C
    common/viewfactors/f11,f12,f13,f21,f22,f23,f31,f32,f33
    common/emmiss/emm1,emm2,emm3
    common/zoneareas/azonel,azone2,azone3
    common/zoneflux/q1,q2,q3
C
    sig = 5.67e-8
C
    ebl = sig*(t1+273)**4.

```

```

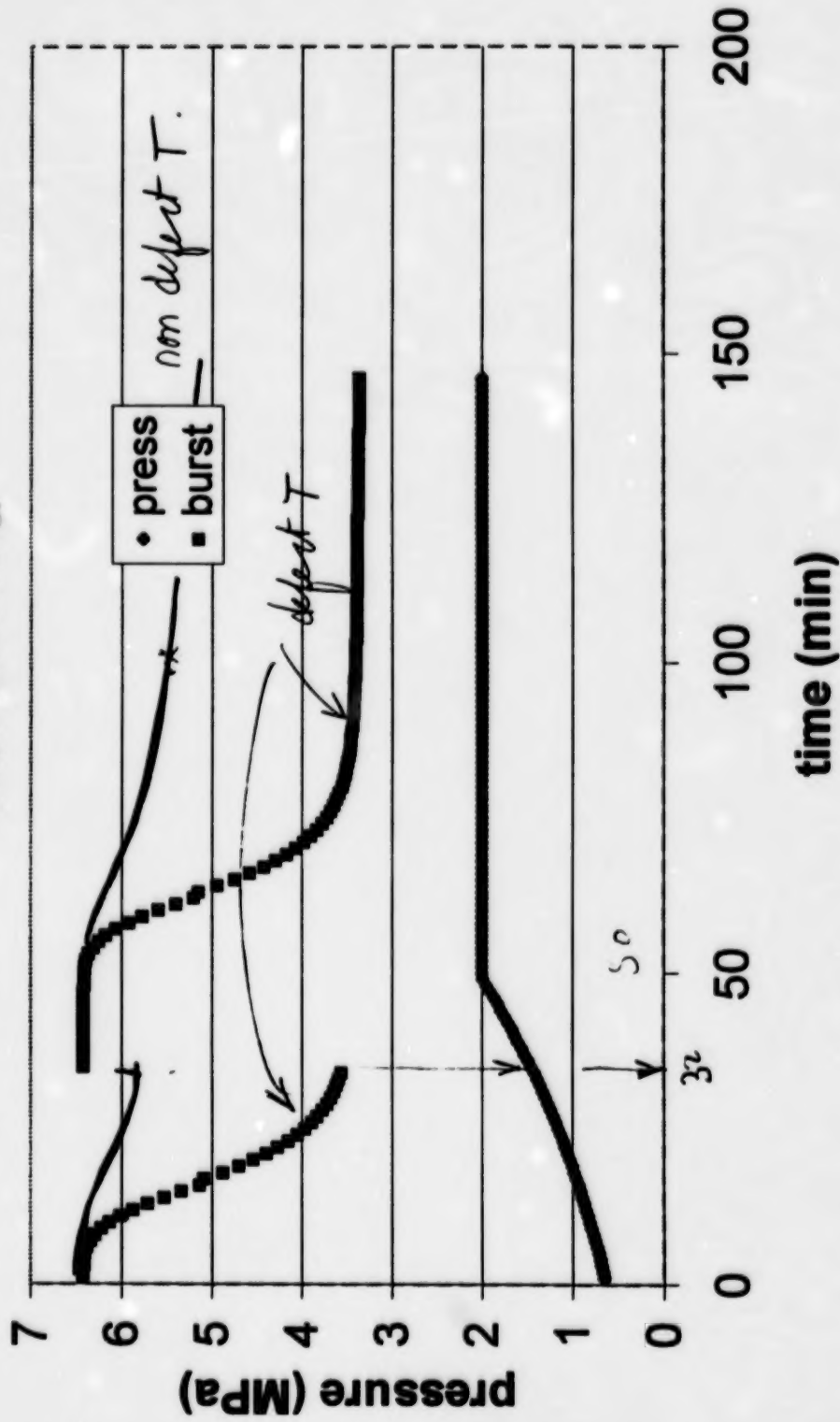
eb2 = sig*(t2+273)**4.
eb3 = sig*(t3+273)**4.
c
sum = 0.0
counter = 0.0
c
100 continue
c
oldsum = sum
counter = counter + 1
if(counter.gt.30) stop 'zones not converging'
j1 = (1-emm1)*(f11*j1 + f12*j2 + f13*j3) + emm1*eb1
j2 = (1-emm2)*(f21*j1 + f22*j2 + f23*j3) + emm2*eb2
j3 = (1-emm3)*(f31*j1 + f32*j2 + f33*j3) + emm3*eb3
c
sum = j1+j2+j3
change = abs((sum - oldsum)/sum)
c
write(*,10) j1,j2,j3,change
if(change.lt.0.001) go to 200
go to 100
c
200 continue
c
q1 = emm1*(eb1-j1)/(1-emm1)
q2 = emm2*(eb2-j2)/(1-emm2)
q3 = emm3*(eb3-j3)/(1-emm3)
c
c
c
write(*,10) j1,j2,j3,q1,q2,q3
c 10 format(2x,6f9.1)
c
return
end
c

```

**Appendix D: Comparison Runs for AFFTAC and TMID**

# press and burst press vs time

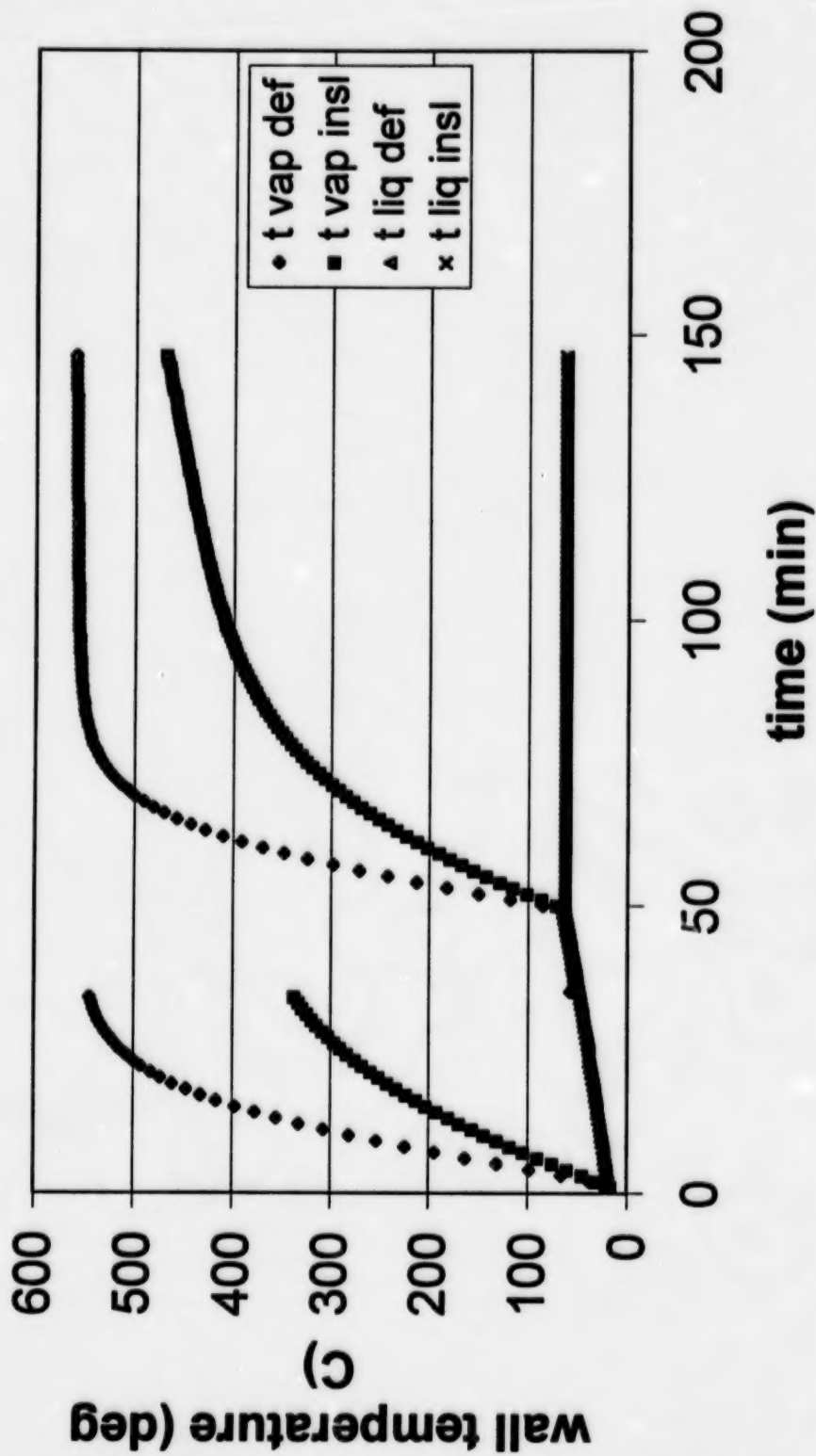
(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-0 deg)





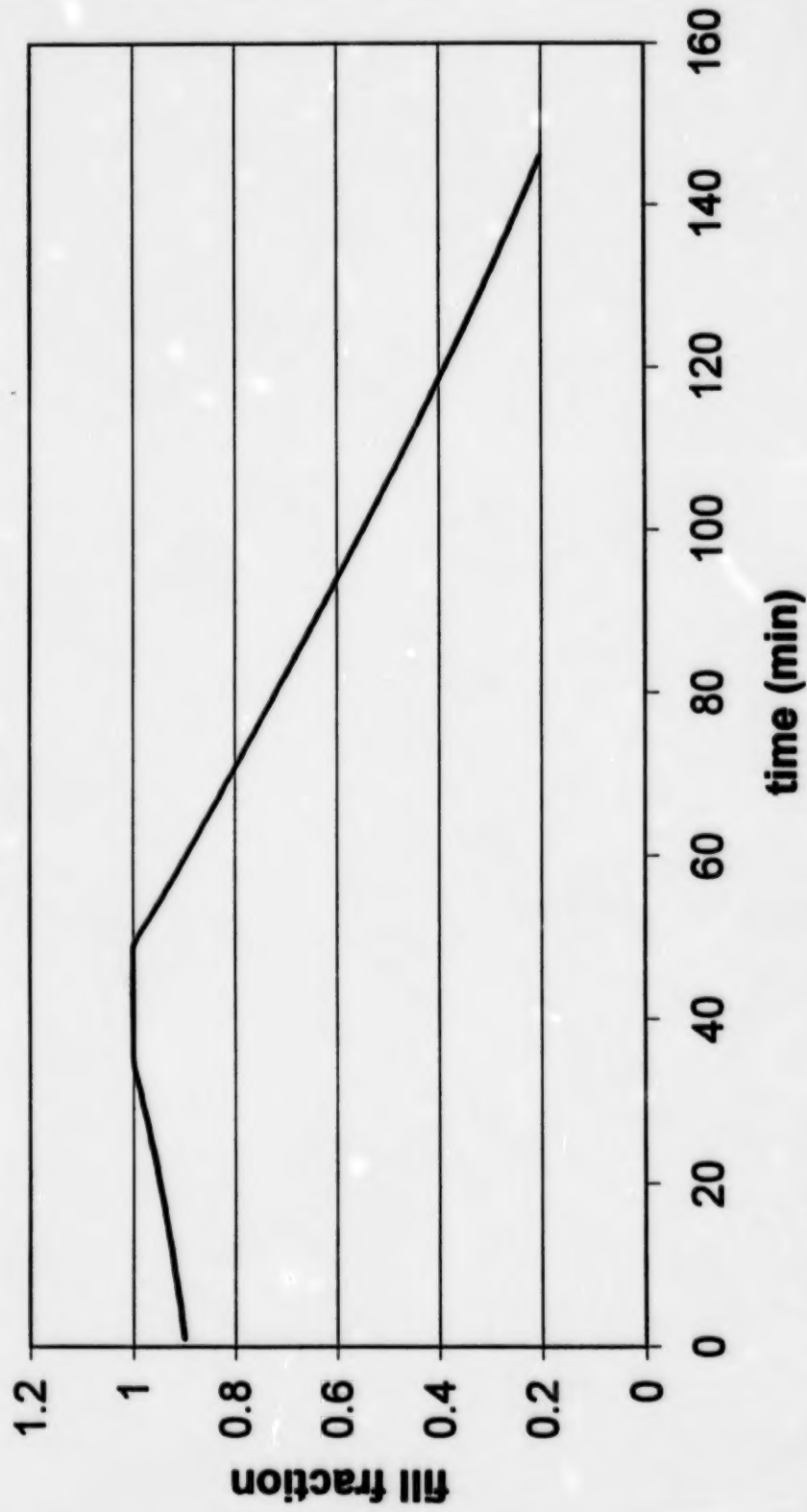
## wall temperatures vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-0 deg)



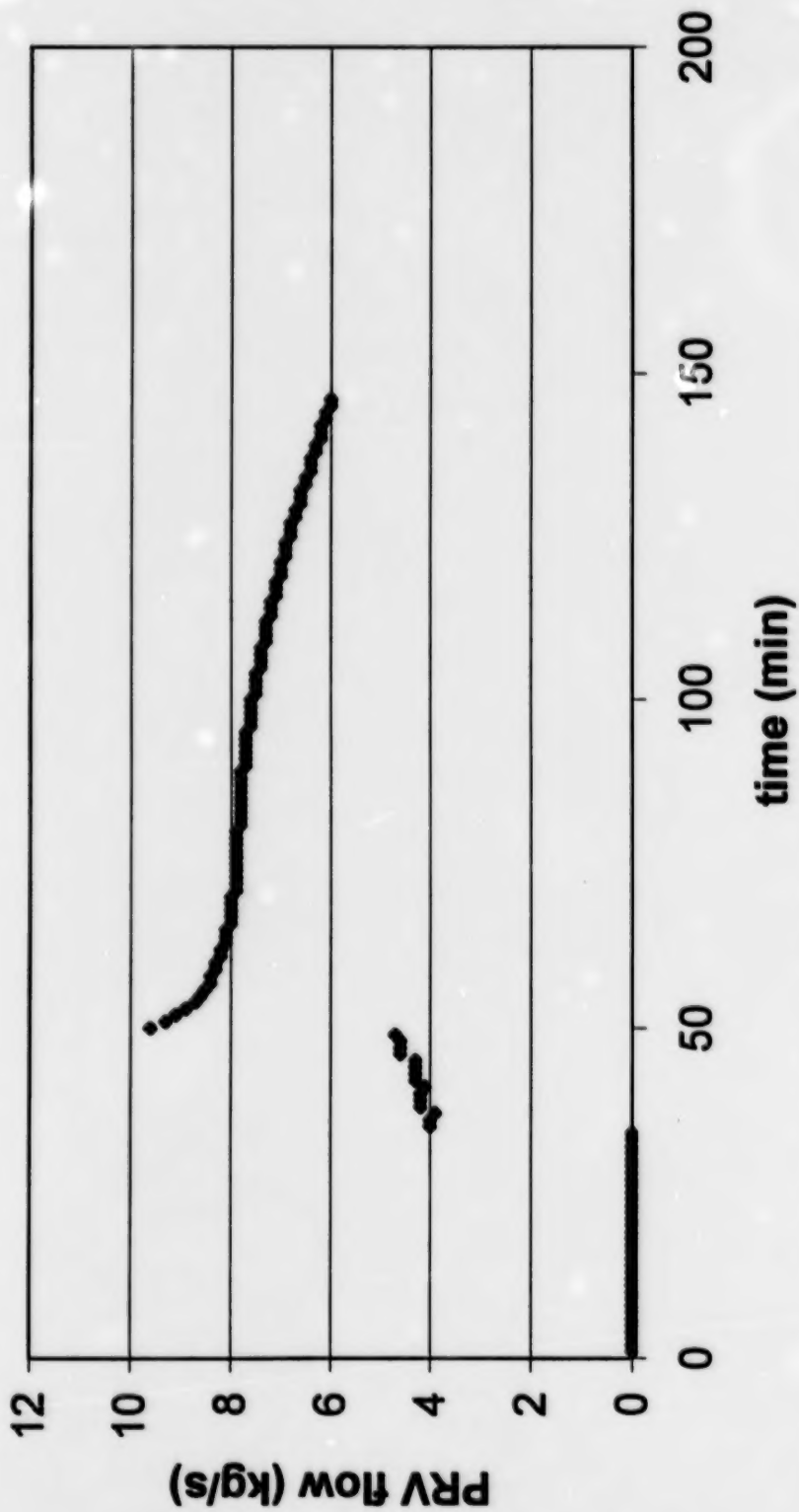
## Fill vs Time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-0 deg)



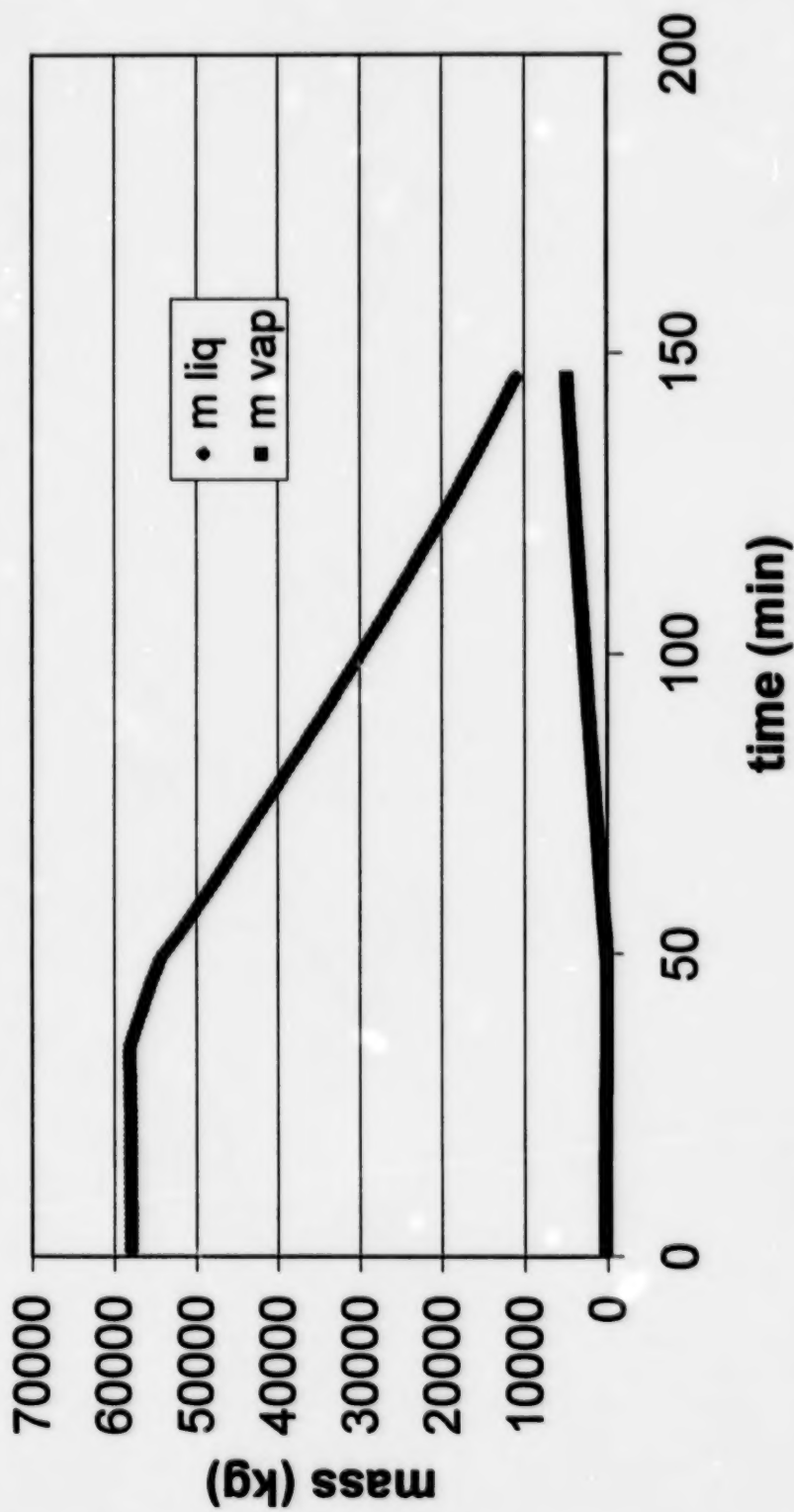
## PRV flow vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-0 deg)

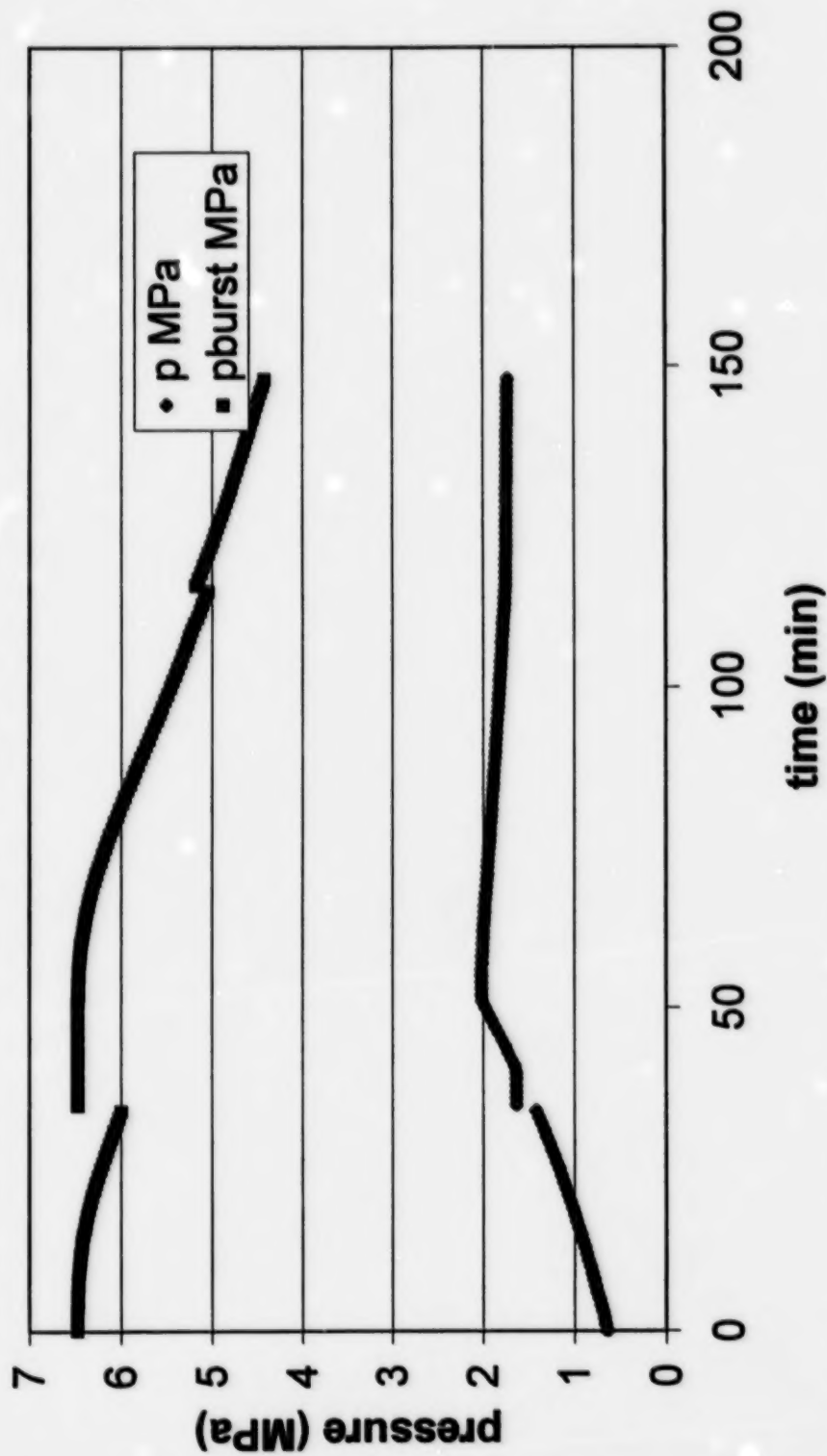


## lading mass vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-0 deg)

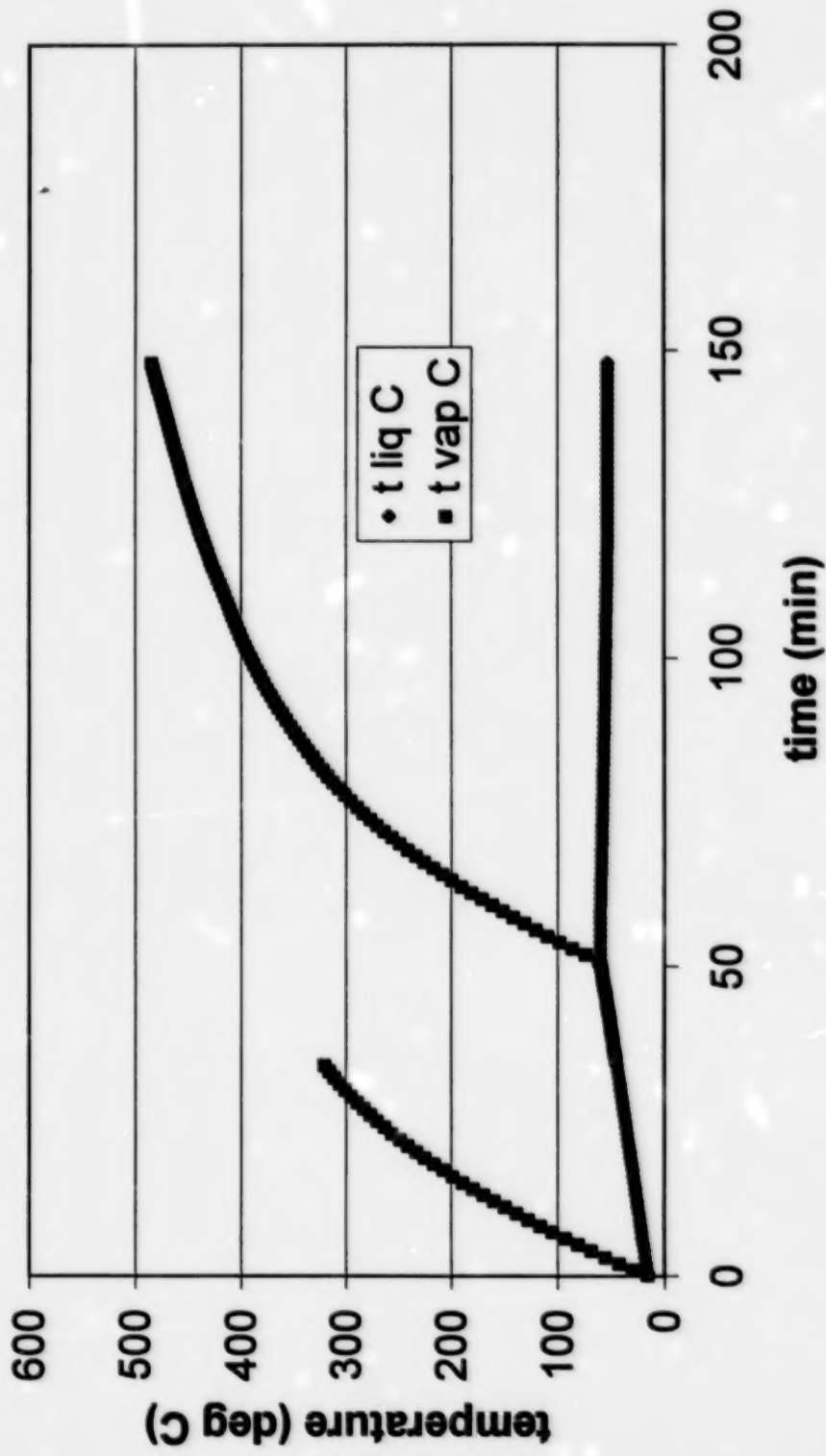


**pressure and burst pressure from AFFTAC**  
(propane, 112 car, 17.5 mm wall, 90% full, 2MPa PRV, 0% defect)



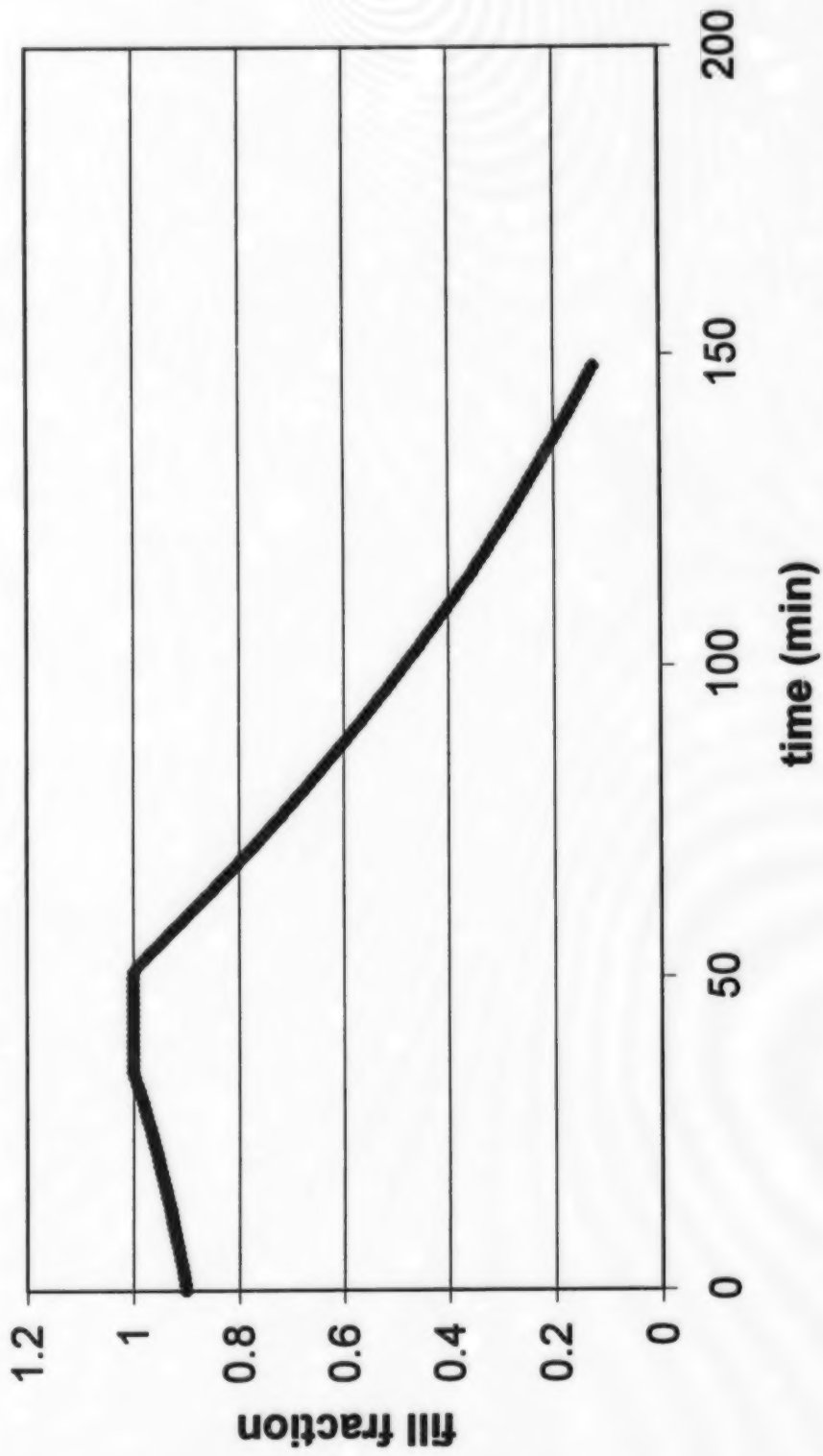
# liquid and vapour temperatures from AFFTAC

(propane, 112 car, 17.5 mm wall, 90% full, 2MPa PRV, 0% defect)

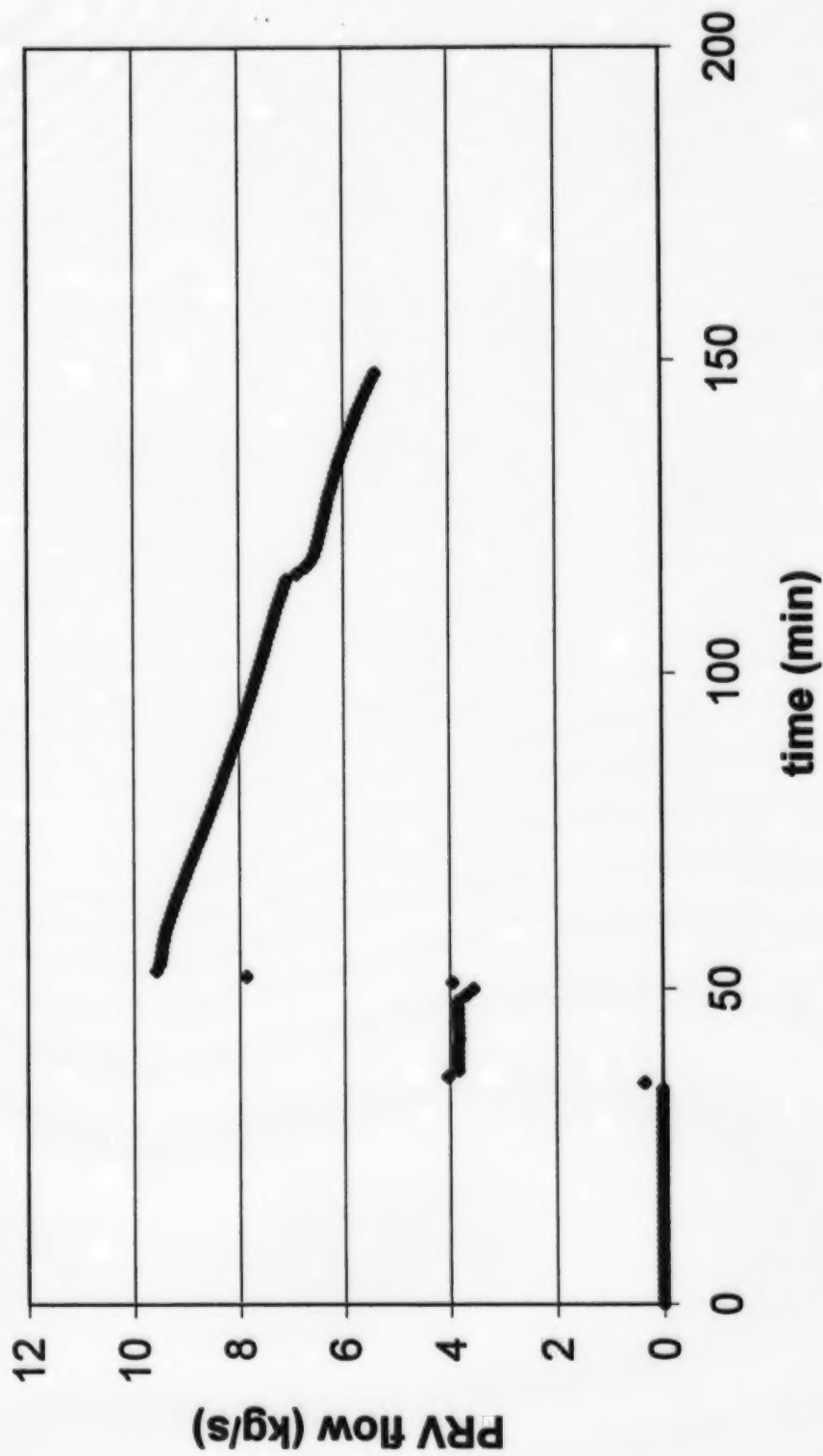




**fill vs time from AFFTAC (propane, 112 car, 17.5 mm wall,  
90% full, 2MPa PRV, 0% defect)**



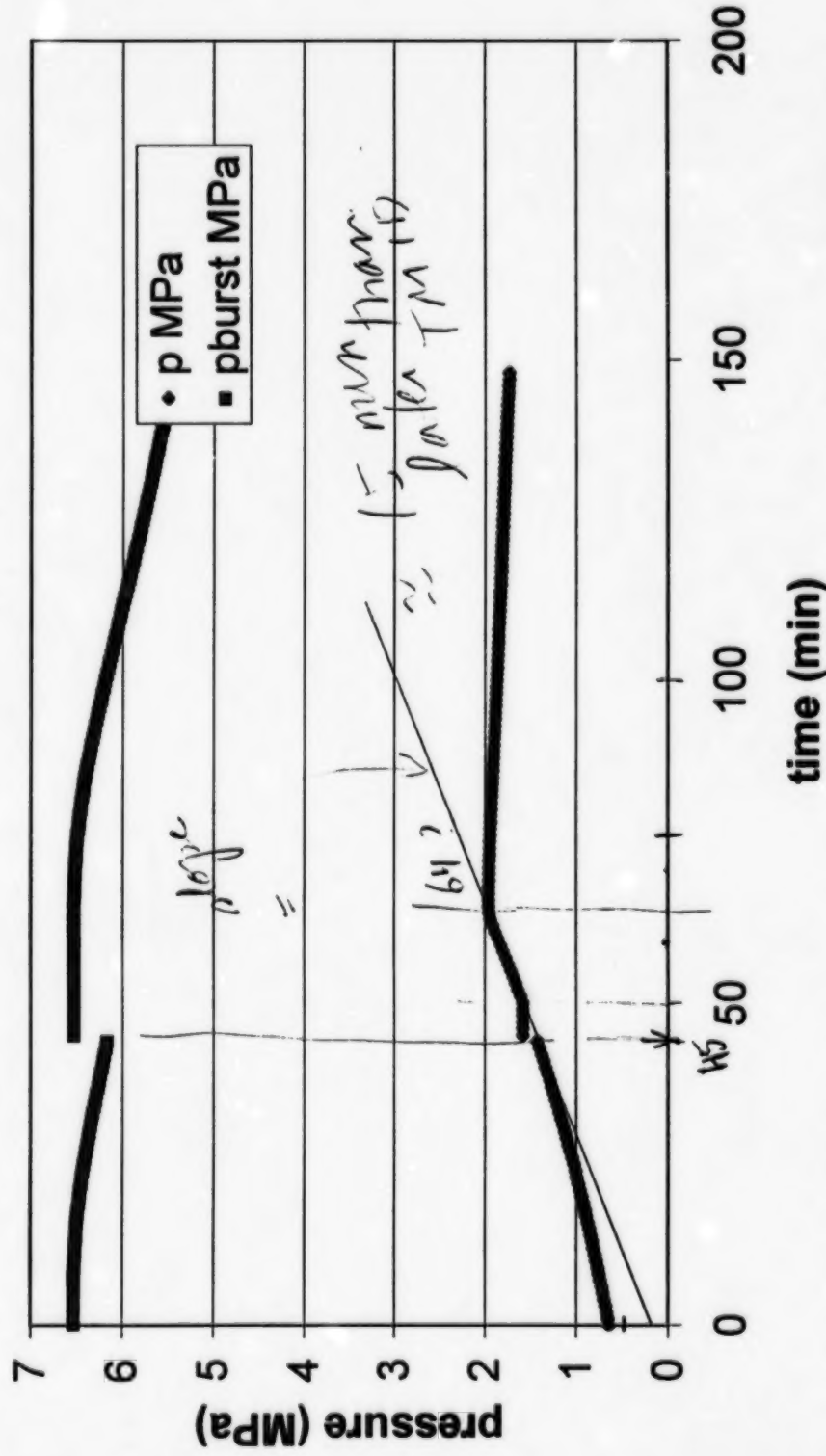
**prv flow vs time from AFFTAC (propane, 112 car, 17.5 mm  
wall, 90% full, 2MPa PRV, 0% defect)**



problem  
with AFFTAC!

# pressure and burst pressure from AFFTAC

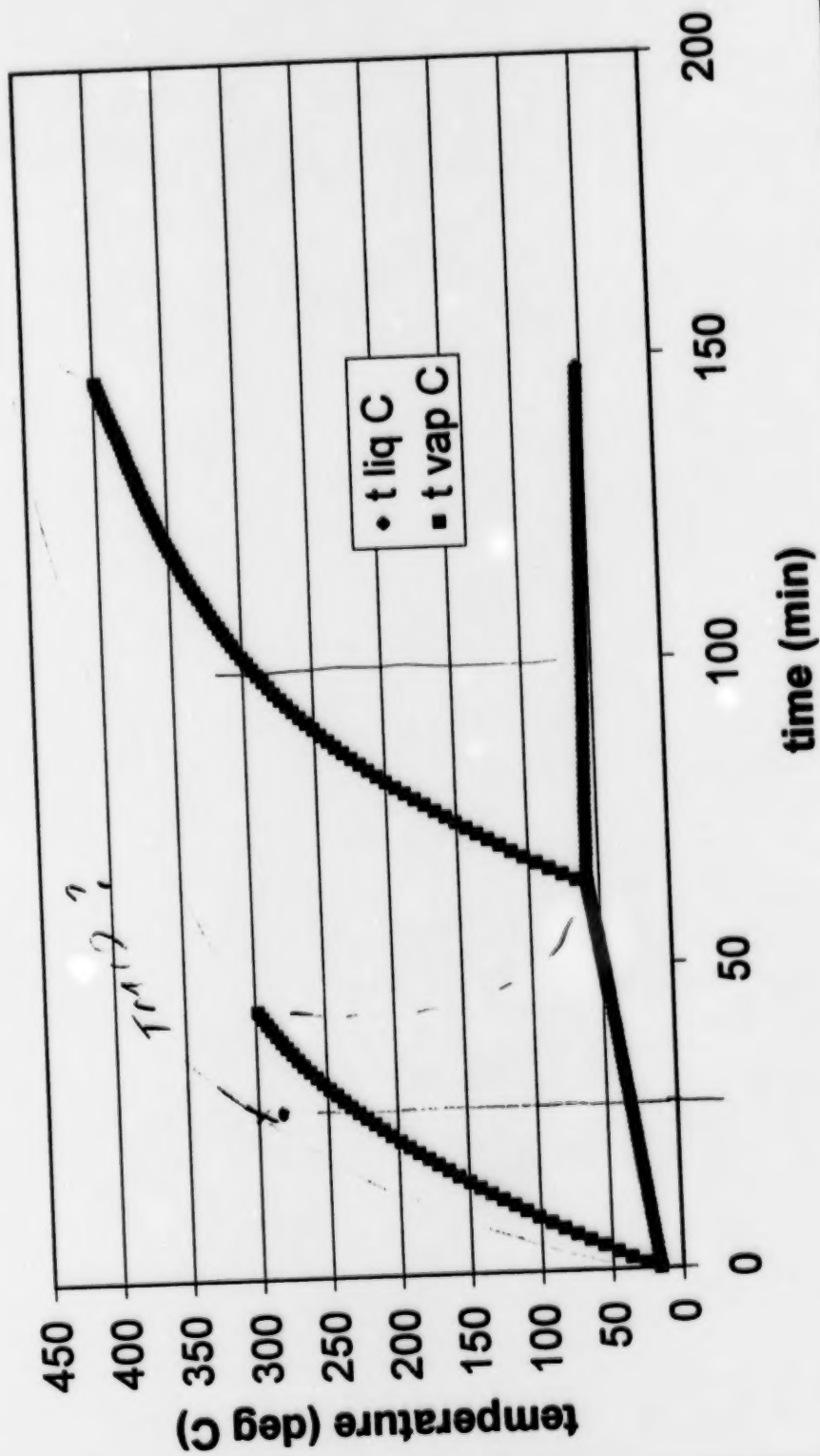
(propane, 112 car, 17.5 mm wall, 90% full, 2MPa PRV, 0% defect)



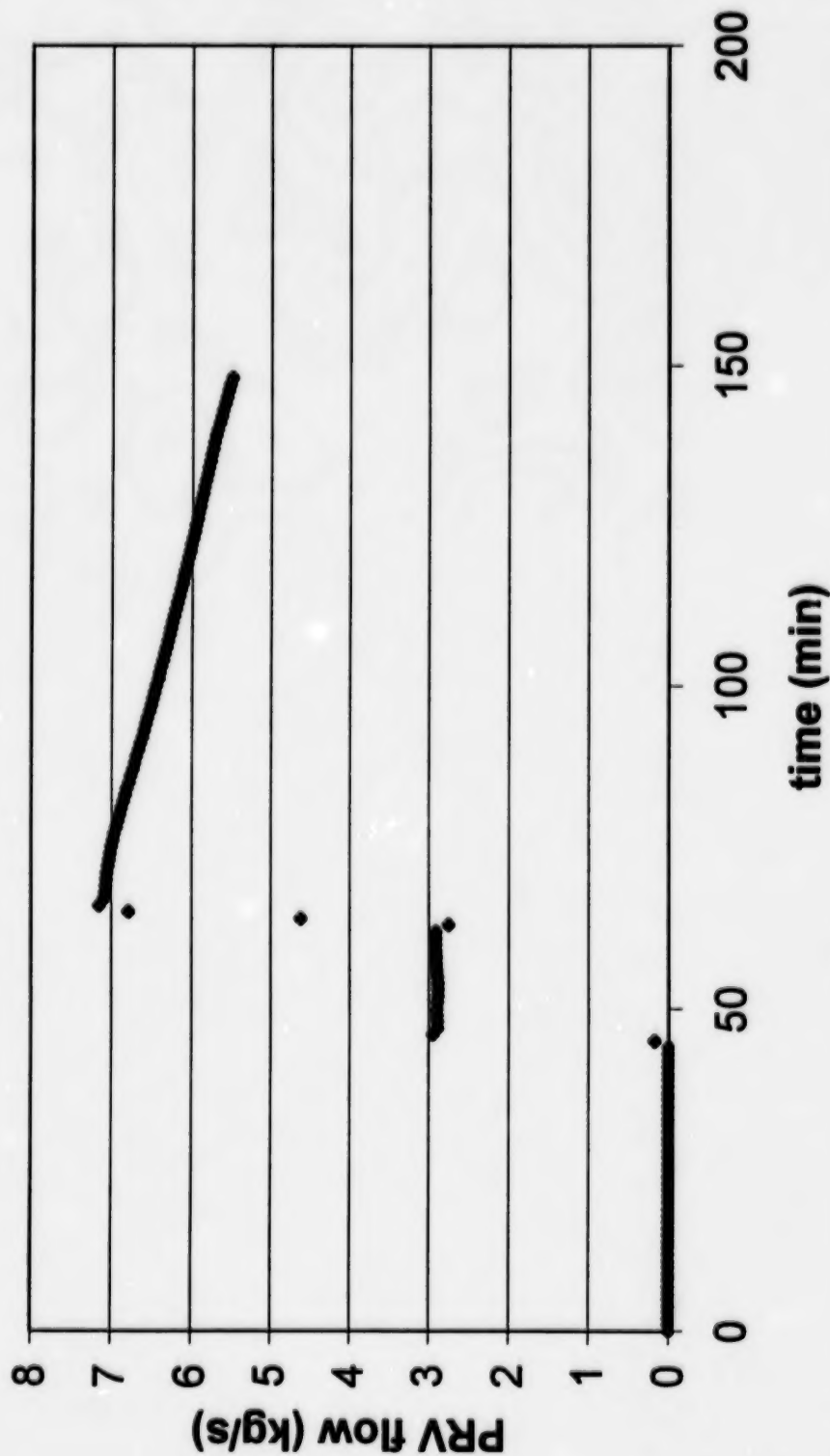
$$\frac{dp}{dt} = 0.0278 \text{ MPa/min}$$

# liquid and vapour temperatures from AFFTAC

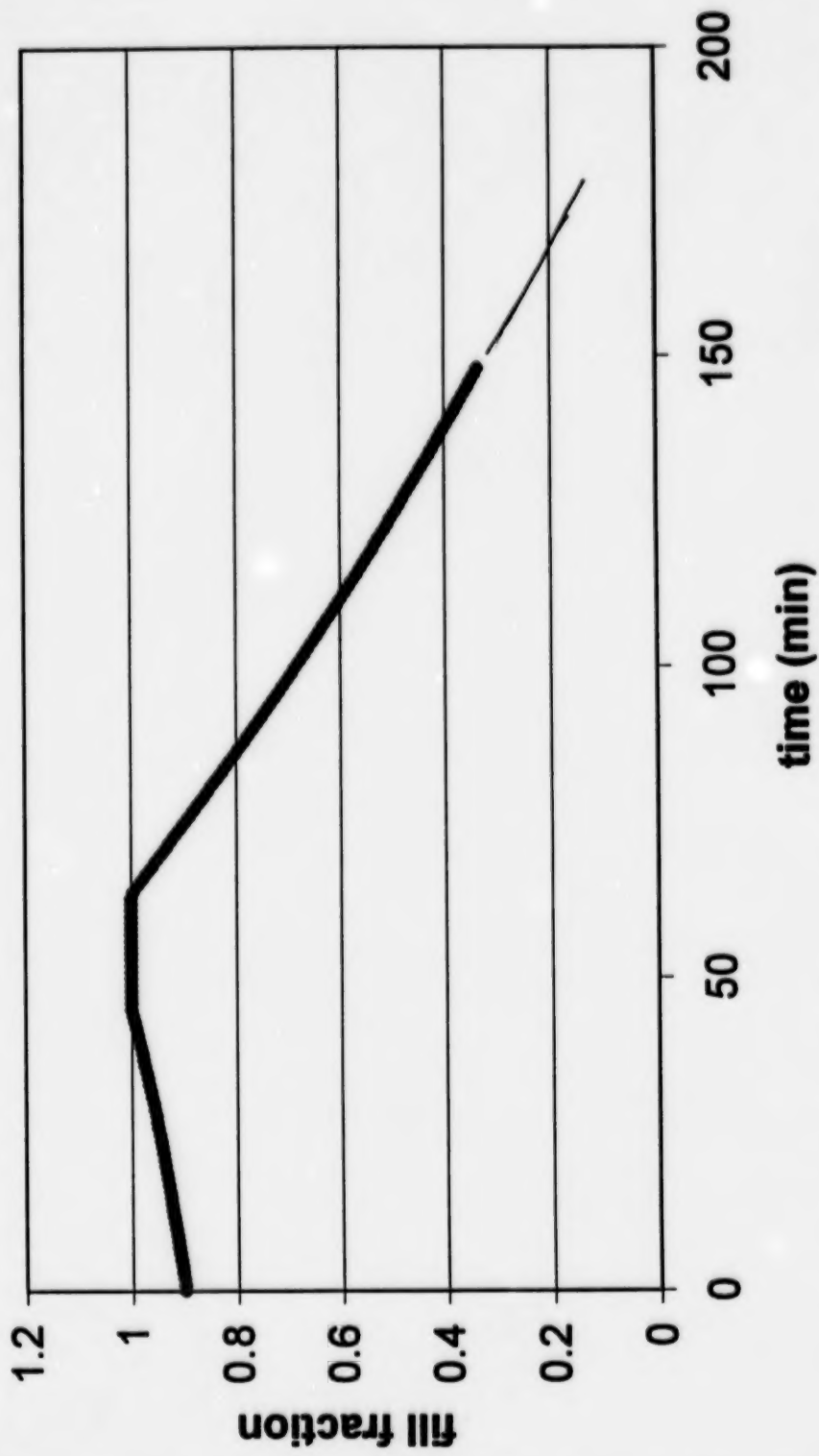
(propane, 112 car, 17.5 mm wall, 90% full, 2MPa PRV, 0% defect)



**prv flow vs time from AFFTAC (propane, 112 car, 17.5 mm  
wall, 90% full, 2MPa PRV, 0% defect)**



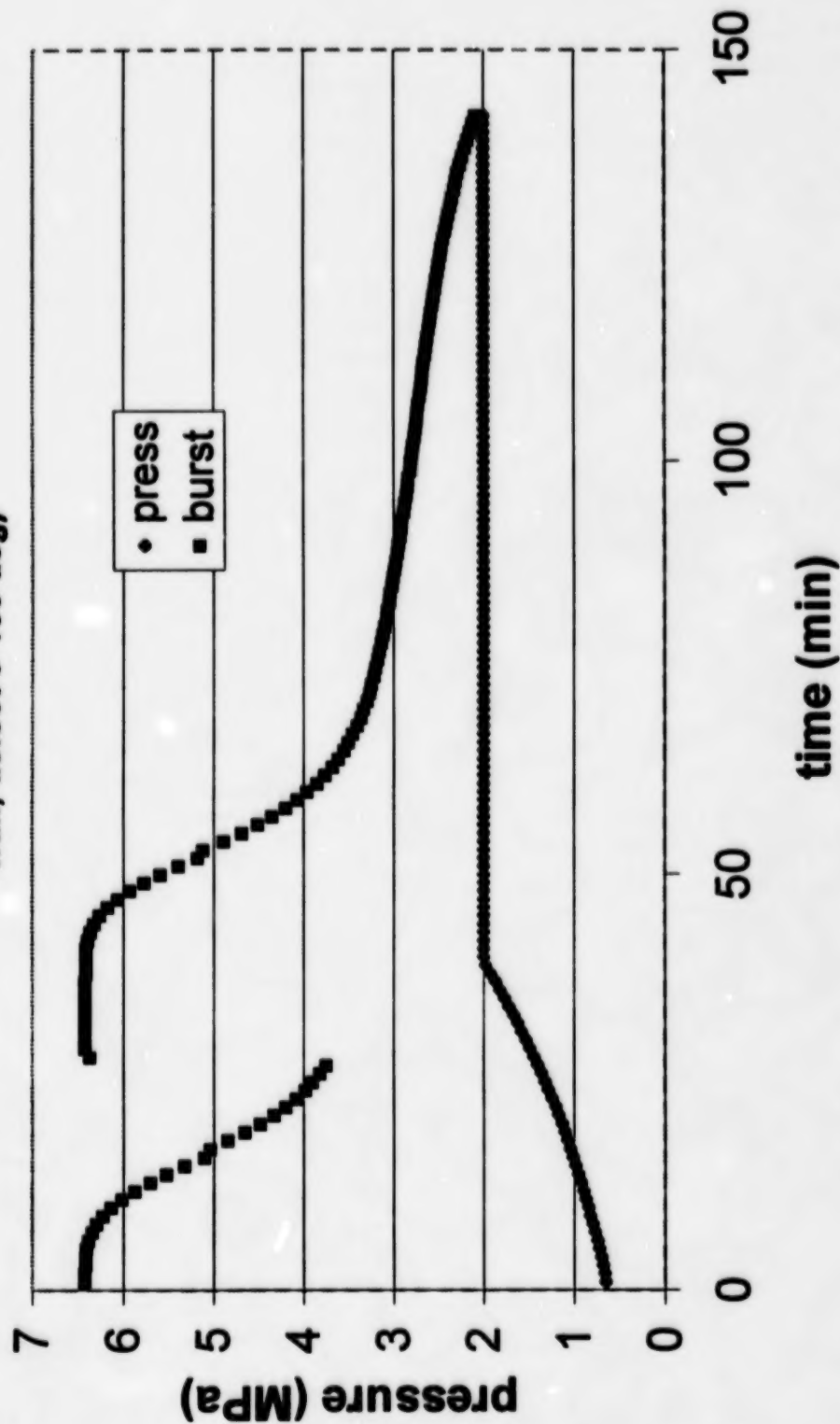
**fill vs time from AFFTAC (propane, 112 car, 17.5 mm wall,  
90% full, 2MPa PRV, 0% defect)**





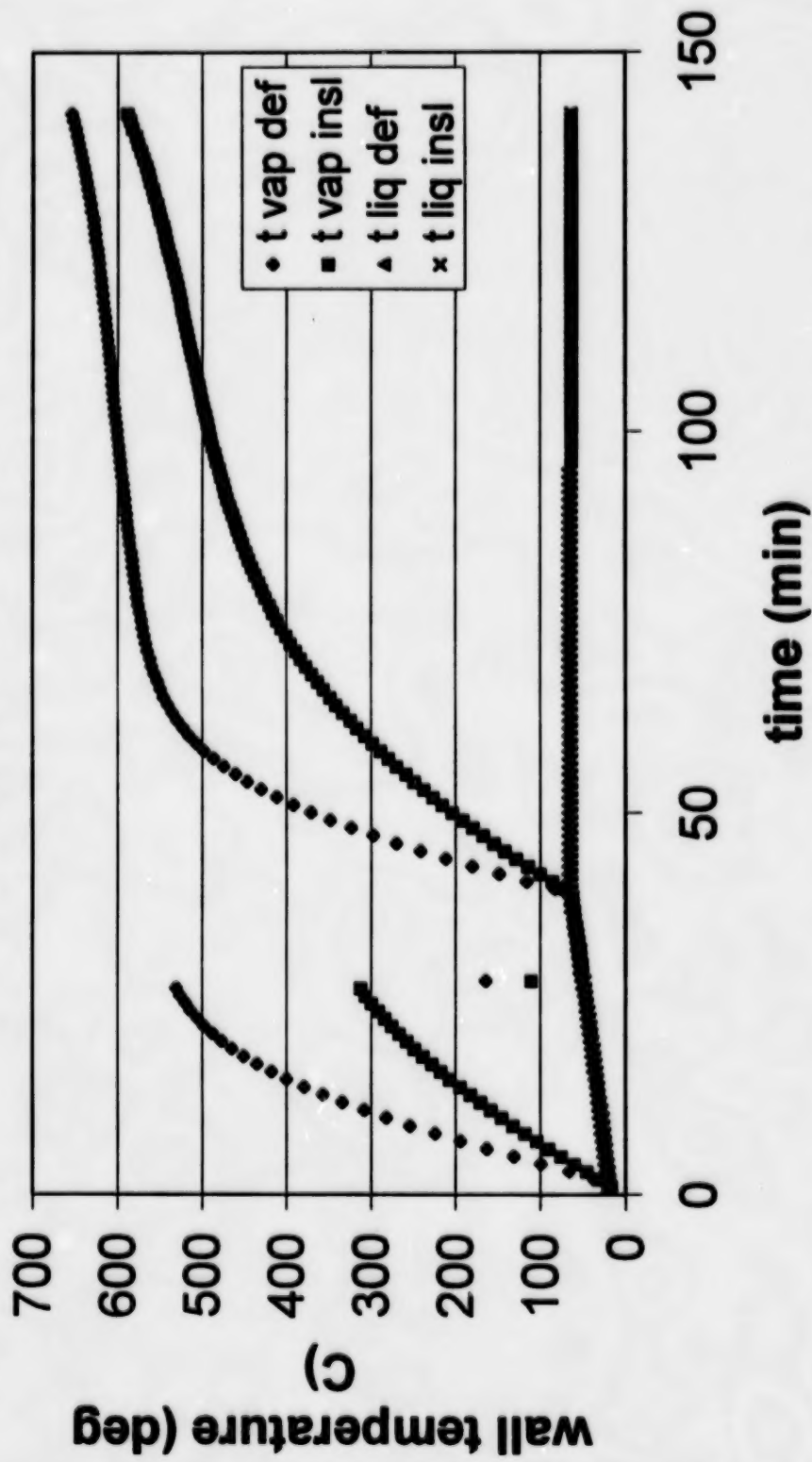
# press and burst press vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-100 deg)



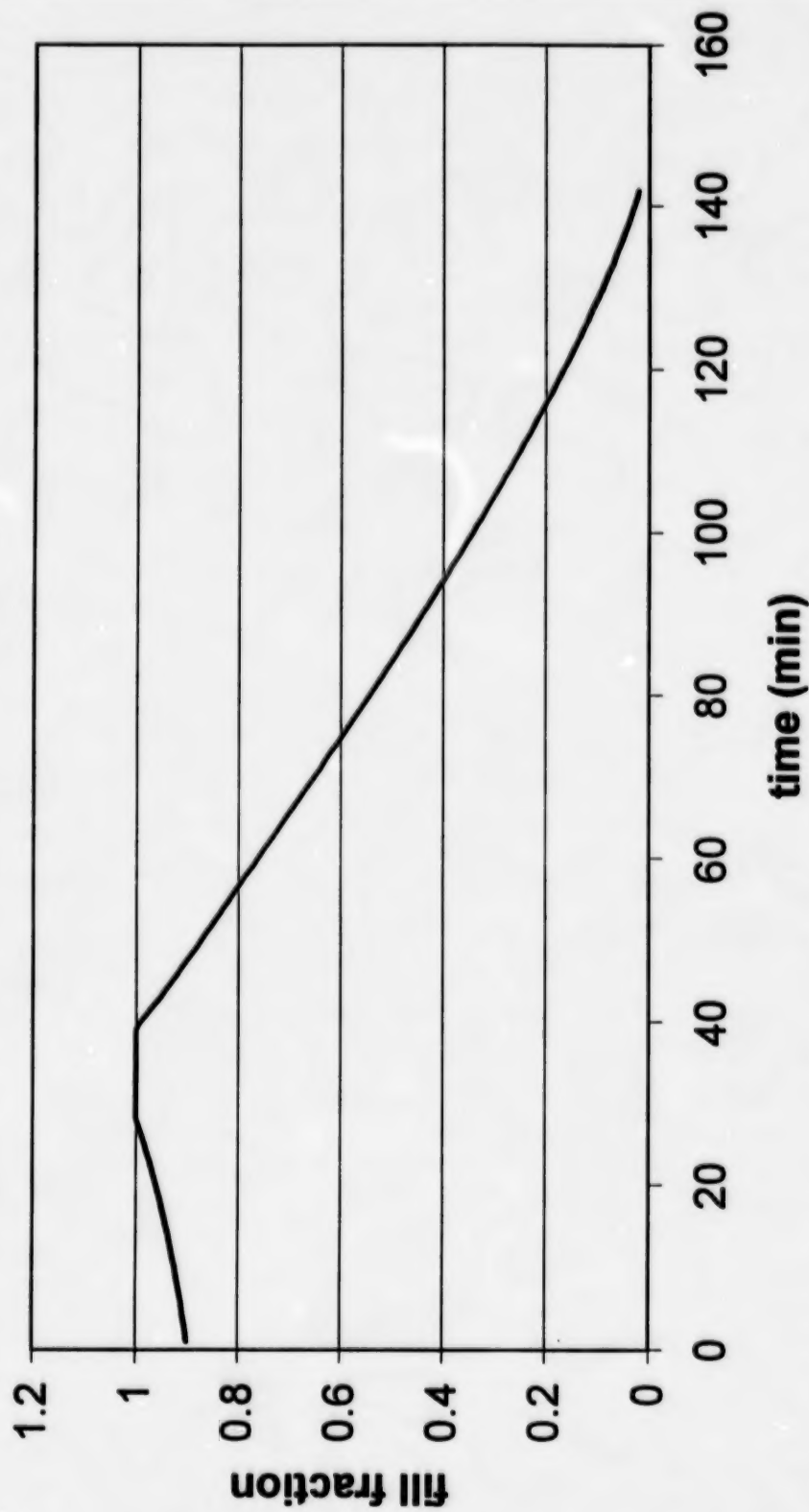
## wall temperatures vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-100 deg)



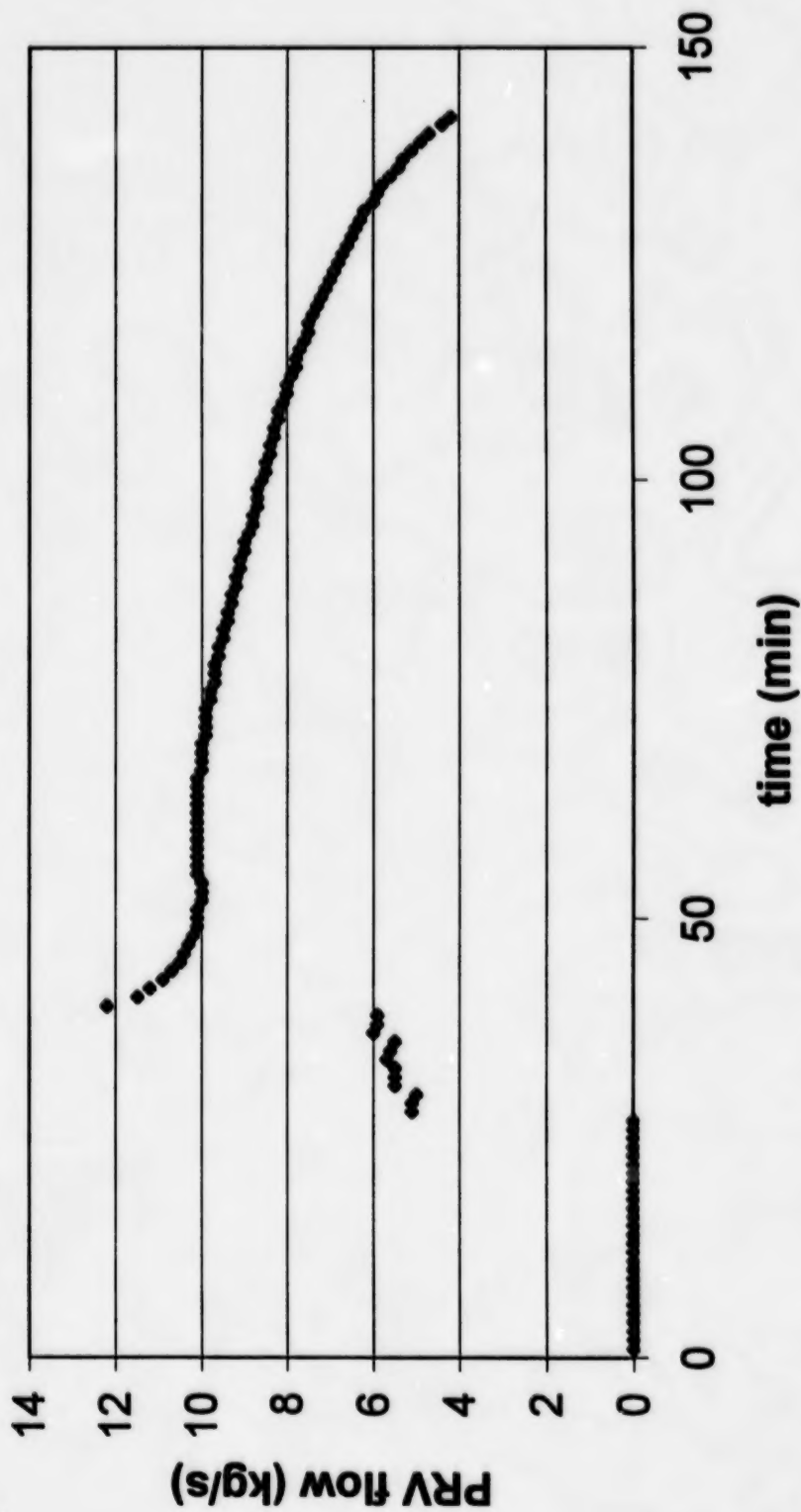
## Fill vs Time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-100 deg)



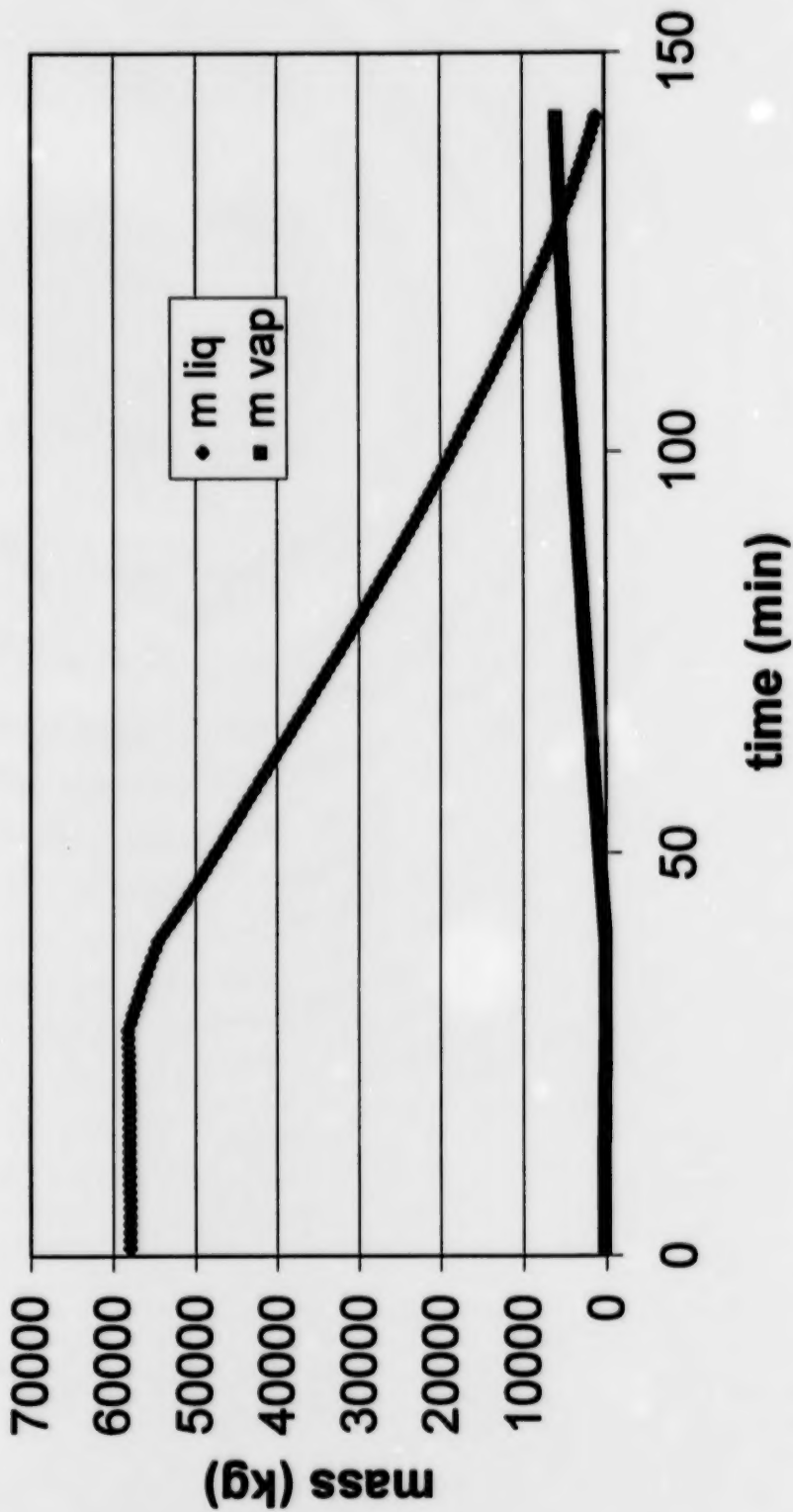
# PRV flow vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-100 deg)



## lading mass vs time

(propane, 112 car, 816 C fire, 90% fill, 15.6 deg C, 2 MPa PRV, 17.5 mm wall, defect 0-100 deg)



**Appendix E: TMID and AFFTAC Simulation Output**



AFFTAC vs TMID

AFFTAC Baseline 0% and 100% defect

DATA ENTERED INTO AFFTAC PROGRAM FOR ANALYSIS  
Program Version 2.0, October 20, 1997

## TANK PARAMETERS

Capacity (gal): 33000.  
Inside Diameter (ins.): 118.00  
Wall Thickness (ins.): .6900  
Tank Material Type: CARBON STEEL  
Tensile Strength of Tank Material (psi): 81000.  
Nominal Burst Strength (psig): 900.0  
Calculated Burst Strength (psig): 947.3  
Angle of Vent or Valve Orientation with Respect  
to Vertical (deg): .00

## PRODUCT DATA

Product Thermal Property Data Contained in Program  
Product Name: PROPANE  
Product Type: Substance  
Initial Fraction of Tank Filled: .900  
Initial Temperature of Product: 60.00  
No Padding Gas Used

## SAFETY RELIEF DEVICE PARAMETERS

Safety Relief Valve Used  
Rated Flow Capacity (SCFM): 25000.  
Flow Rating Pressure (psig): 280.50  
Start-to-Discharge Pressure (psig): 255.00  
Vent or Valve Vapor Flow Discharge Coefficient: .80  
Vent or Valve Liquid Flow Discharge Coefficient: .80

## THERMAL PROTECTION SYSTEM CHARACTERISTICS

Jacketed Insulation System Not Resistant  
to High Temperature Effects  
Initial Conductance (BTU/hr-sq.ft-deg F): 4.00  
Time Interval for Linear Change from Initial Conductance  
to Steady State Conductance (min): 10000.00

Discontinuities in Insulation Not Considered

No Tank Lining Used

## FIRE CONDITIONS

Standard Pool Fire Simulation Analysis  
Flame Temperature (deg F): 1500.0  
Fraction of Tank Surface Subject to Heat Input: 1.00  
Tank Radiation Emissivity Coefficient: .90

## ANALYSIS CONDITIONS

Time Limit (min): 300.00  
 Time Increment for Analysis (min): .10  
 Time Increments Between Display of Output Data: 10

THERMAL PROPERTY DATA CONTAINED IN PROGRAM  
FOR PROPANE

Temperature (degrees F), Vapor Pressure (psia), Specific Heat (BTU/lb-deg F), Specific Volume (cu. ft/lb), Heat of Vaporization (BTU/lb), Compressibility Factor of Vapor, and Ratio of Specific Heats of Vapor

Temp.	Vapor Pres.	Spec. Heat	Spec. Volume	Heat of Vap.	Vapor Comp. Fact.	Vapor Ratio of Spec. Heats
.00	38.32	.5539	.02946	170.4	.92	1.18
20.00	55.54	.5683	.03011	164.2	.90	1.21
40.00	78.78	.5855	.03076	158.0	.87	1.24
60.00	108.08	.6066	.03148	151.6	.84	1.26
80.00	144.68	.6331	.03259	143.3	.81	1.29
100.00	189.61	.6678	.03391	134.0	.77	1.37
120.00	244.39	.7236	.03549	123.2	.72	1.44
140.00	309.20	.7828	.03731	110.9	.68	1.52
160.00	386.18	.8788	.03984	95.9	.60	1.63
180.00	476.16	1.0683	.04351	75.2	.51	1.75
200.00	580.81	1.7230	.05252	35.3	.38	4.68

MOLECULAR WEIGHT: 44.00

## PRODUCT: PROPANE

TIME (min.)	TEMPERATURES (deg F)		PRESSURES		MASS FRACT. IN TANK	FILLED FRACT. OF TANK	RATE OF PRODUCT RELEASE (lbs/min)
	LIQ. PROD.	TANK VAPOR	WITHIN TANK (psi)	BURST STR. (psi)			
.0	60.0	60.0	93.4	947.3	1.000	.900	.0
1.0	61.1	78.4	95.1	947.3	1.000	.901	.0
2.0	62.3	96.4	97.0	947.3	1.000	.903	.0
3.0	63.5	114.1	99.0	947.2	1.000	.905	.0
4.0	64.6	131.5	100.9	947.1	1.000	.906	.0
5.0	65.8	148.5	102.9	947.1	1.000	.908	.0
6.0	66.9	165.3	105.0	946.9	1.000	.910	.0
7.0	68.1	181.7	107.0	946.7	1.000	.912	.0
8.0	69.2	197.8	109.1	946.5	1.000	.913	.0
9.0	70.4	213.5	111.2	946.2	1.000	.915	.0
10.0	71.5	228.9	113.3	945.9	1.000	.917	.0
11.0	72.7	244.0	115.5	945.5	1.000	.919	.0
12.0	73.9	258.8	117.7	945.0	1.000	.921	.0
13.0	75.0	273.2	119.9	944.4	1.000	.923	.0
14.0	76.2	287.3	122.2	943.8	1.000	.925	.0
15.0	77.4	301.1	124.5	943.1	1.000	.927	.0
16.0	78.5	314.6	126.8	942.3	1.000	.929	.0
17.0	79.7	327.7	129.2	941.4	1.000	.931	.0
18.0	80.9	340.5	131.5	940.4	1.000	.933	.0
19.0	82.1	353.0	133.9	939.4	1.000	.935	.0
20.0	83.2	365.1	136.4	938.2	1.000	.937	.0
21.0	84.4	377.0	138.8	937.0	1.000	.939	.0
22.0	85.6	388.5	141.3	935.6	1.000	.941	.0
23.0	86.8	399.7	143.9	934.2	1.000	.943	.0
24.0	88.0	410.6	146.5	932.8	1.000	.945	.0
25.0	89.2	421.1	149.1	931.2	1.000	.947	.0
26.0	90.4	431.4	151.7	929.6	1.000	.950	.0
27.0	91.5	441.4	154.5	927.9	1.000	.952	.0
28.0	92.7	451.0	157.2	926.1	1.000	.954	.0
29.0	93.9	460.4	160.0	924.3	1.000	.957	.0
30.0	95.1	469.4	162.8	922.5	1.000	.959	.0
31.0	96.3	478.2	165.7	920.6	1.000	.962	.0
32.0	97.5	486.7	168.6	918.6	1.000	.964	.0
33.0	98.7	494.9	171.5	916.6	1.000	.967	.0
34.0	99.9	502.8	174.5	914.6	1.000	.969	.0
35.0	101.2	510.4	177.5	912.6	1.000	.972	.0
36.0	102.4	517.8	180.6	910.5	1.000	.975	.0
37.0	103.6	524.9	183.7	908.5	1.000	.977	.0
38.0	104.8	531.7	186.8	906.4	1.000	.980	.0
39.0	106.0	538.3	190.0	904.3	1.000	.983	.0
40.0	107.2	544.7	193.2	902.3	1.000	.986	.0
41.0	108.4	550.7	196.5	900.2	1.000	.988	.0
42.0	109.7	556.6	199.8	898.2	1.000	.991	.0
43.0	110.9	562.2	203.2	896.2	1.000	.994	.0

44.0	112.1	567.5	206.6	894.2	1.000	.997	.0
45.0	113.4	113.3	210.6	947.2	1.000	1.000	22.7
46.0	114.7	114.6	214.4	947.2	.997	1.000	399.9
47.0	116.0	115.9	218.1	947.2	.994	1.000	379.0
48.0	117.3	117.2	221.8	947.2	.991	1.000	379.0
49.0	118.6	118.4	225.6	947.2	.988	1.000	379.5
50.0	119.9	119.7	229.4	947.2	.985	1.000	379.8
51.0	121.1	121.0	233.2	947.2	.982	1.000	380.1
52.0	122.4	122.3	237.1	947.2	.979	1.000	380.3
53.0	123.7	123.6	241.0	947.2	.976	1.000	380.3
54.0	124.9	124.8	244.9	947.2	.973	1.000	380.8
55.0	126.2	126.1	248.9	947.2	.970	1.000	381.7
56.0	127.5	127.4	252.9	947.2	.967	1.000	382.4
57.0	128.7	128.6	256.7	947.2	.964	1.000	392.4
58.0	129.1	146.5	257.7	947.1	.958	.994	722.6
59.0	129.1	163.9	257.9	946.9	.951	.986	909.2
60.0	129.1	180.7	257.8	946.8	.943	.978	912.8
61.0	129.1	197.1	257.8	946.5	.936	.969	907.8
62.0	129.0	212.9	257.7	946.2	.929	.961	907.2
63.0	129.0	228.2	257.5	945.9	.922	.953	906.2
64.0	128.9	243.1	257.3	945.5	.915	.944	904.9
65.0	128.9	257.5	257.1	945.0	.908	.936	903.4
66.0	128.8	271.5	256.9	944.5	.901	.928	901.7
67.0	128.7	285.0	256.6	943.9	.893	.919	899.8
68.0	128.6	298.0	256.3	943.3	.886	.911	897.8
69.0	128.5	310.7	256.0	942.5	.879	.902	895.6
70.0	128.4	323.8	255.7	941.7	.872	.894	893.3
71.0	128.3	337.0	255.3	940.7	.865	.886	890.6
72.0	128.2	349.8	254.9	939.6	.858	.877	887.7
73.0	128.0	362.3	254.5	938.5	.851	.869	884.7
74.0	127.9	374.5	254.0	937.2	.844	.861	881.6
75.0	127.8	386.3	253.6	935.9	.837	.853	878.6
76.0	127.6	397.7	253.2	934.5	.830	.844	875.5
77.0	127.5	408.9	252.8	933.0	.823	.836	872.3
78.0	127.3	419.7	252.3	931.4	.817	.828	869.2
79.0	127.2	430.2	251.9	929.8	.810	.820	866.0
80.0	127.1	440.4	251.5	928.1	.803	.812	862.9
81.0	126.9	450.3	251.0	926.3	.796	.804	859.7
82.0	126.8	459.9	250.6	924.4	.789	.796	856.6
83.0	126.7	469.2	250.2	922.5	.783	.788	853.5
84.0	126.5	478.3	249.7	920.5	.776	.780	850.4
85.0	126.4	487.0	249.3	918.5	.769	.772	847.4
86.0	126.3	495.5	248.9	916.5	.763	.764	844.4
87.0	126.1	503.8	248.5	914.3	.756	.757	841.4
88.0	126.0	511.8	248.0	912.2	.749	.749	838.4
89.0	125.9	519.5	247.6	910.0	.743	.741	835.5
90.0	125.7	527.0	247.2	907.8	.736	.733	832.7
91.0	125.6	534.3	246.8	905.6	.730	.726	829.9
92.0	125.5	541.3	246.5	903.4	.723	.718	827.1
93.0	125.4	548.1	246.1	901.1	.716	.711	824.4
94.0	125.2	554.8	245.7	898.9	.710	.703	821.7



95.0	125.1	561.2	245.3	896.6	.704	.696	819.1
96.0	125.0	567.4	245.0	894.3	.697	.688	816.5
97.0	124.9	573.4	244.6	892.0	.691	.681	813.9
98.0	124.8	579.2	244.2	889.7	.684	.673	811.5
99.0	124.7	584.8	243.9	887.5	.678	.666	809.0
100.0	124.5	590.3	243.6	885.2	.671	.658	806.6
101.0	124.4	595.6	243.2	882.9	.665	.651	804.3
102.0	124.3	600.8	242.9	880.7	.659	.644	801.9
103.0	124.2	605.7	242.6	878.4	.652	.637	799.7
104.0	124.1	610.6	242.2	876.2	.646	.629	797.4
105.0	124.0	615.2	241.9	874.0	.640	.622	795.2
106.0	123.9	619.8	241.6	871.8	.634	.615	793.1
107.0	123.8	624.2	241.3	869.6	.627	.608	790.9
108.0	123.7	628.5	241.0	867.5	.621	.601	788.9
109.0	123.6	633.2	240.7	865.1	.615	.594	786.7
110.0	123.5	637.8	240.3	862.7	.609	.586	784.2
111.0	123.4	642.2	240.0	860.3	.603	.579	781.8
112.0	123.3	646.6	239.6	857.9	.596	.572	779.5
113.0	123.2	650.8	239.3	855.5	.590	.565	777.2
114.0	123.1	654.9	238.9	853.2	.584	.558	774.9
115.0	122.9	658.9	238.6	850.9	.578	.551	772.7
116.0	122.8	662.8	238.3	848.6	.572	.545	770.5
117.0	122.7	666.5	238.0	846.3	.566	.538	768.3
118.0	122.6	670.2	237.7	844.1	.560	.531	766.2
119.0	122.5	673.8	237.4	841.9	.554	.524	764.1
120.0	122.4	677.3	237.1	839.7	.548	.517	762.0
121.0	122.3	680.7	236.8	837.5	.542	.510	760.0
122.0	122.2	684.0	236.5	835.3	.536	.504	757.9
123.0	122.1	687.2	236.2	833.2	.530	.497	755.9
124.0	122.0	690.3	235.9	831.1	.524	.490	753.9
125.0	121.9	693.4	235.6	829.0	.518	.483	752.0
126.0	121.8	696.4	235.3	827.0	.512	.477	750.0
127.0	121.7	699.3	235.0	824.9	.506	.470	748.0
128.0	121.7	702.2	234.7	822.9	.500	.463	746.1
129.0	121.6	705.0	234.4	820.9	.494	.457	744.1
130.0	121.5	707.7	234.1	819.0	.488	.450	742.2
131.0	121.4	710.4	233.8	817.0	.483	.444	740.2
132.0	121.3	713.0	233.5	815.1	.477	.437	738.2
133.0	121.2	715.6	233.2	813.2	.471	.430	736.3
134.0	121.1	718.1	232.9	811.3	.465	.424	734.3
135.0	121.0	720.6	232.6	809.4	.459	.417	732.3
136.0	120.9	723.0	232.3	807.5	.454	.411	730.3
137.0	120.8	725.4	232.0	805.6	.448	.405	728.3
138.0	120.6	727.9	231.7	803.7	.442	.398	726.2
139.0	120.5	730.9	231.2	801.3	.436	.392	723.8
140.0	120.4	733.9	230.8	798.9	.431	.385	721.0
141.0	120.2	736.8	230.4	796.6	.425	.379	718.3
142.0	120.1	739.6	230.0	794.2	.419	.373	715.6
143.0	120.0	742.4	229.6	791.9	.414	.366	713.0
144.0	119.8	745.1	229.2	789.6	.408	.360	710.3
145.0	119.7	747.8	228.8	787.3	.403	.354	707.7

146.0	119.5	750.4	228.4	785.1	.397	.348	705.1
147.0	119.4	753.0	228.0	782.8	.391	.342	702.5
148.0	119.3	755.6	227.6	780.6	.386	.336	699.8
149.0	119.1	758.1	227.2	778.3	.380	.329	697.2
150.0	119.0	760.6	226.8	776.1	.375	.323	694.6
151.0	118.9	763.1	226.3	773.9	.369	.317	692.0
152.0	118.7	765.5	225.9	771.7	.364	.311	689.4
153.0	118.6	767.9	225.5	769.5	.359	.305	686.7
154.0	118.4	770.2	225.1	767.3	.353	.299	684.1
155.0	118.3	772.6	224.7	765.1	.348	.293	681.4
156.0	118.1	774.9	224.2	762.9	.342	.288	677.7
157.0	118.1	777.2	223.9	760.7	.337	.282	663.7
158.0	118.0	779.4	223.8	758.5	.332	.276	652.6
159.0	118.0	781.7	223.7	756.3	.327	.271	645.7
160.0	117.9	783.9	223.6	754.2	.322	.265	641.1
161.0	117.9	786.1	223.5	752.0	.317	.259	637.6
162.0	117.9	788.3	223.4	749.8	.312	.254	634.6
163.0	117.9	790.4	223.4	747.6	.307	.248	631.9
164.0	117.9	792.6	223.3	745.4	.302	.243	629.3
165.0	117.8	794.7	223.3	743.2	.297	.237	626.6
166.0	117.8	796.9	223.2	741.0	.292	.232	624.0
167.0	117.8	799.0	223.2	738.8	.287	.227	621.3
168.0	117.8	801.1	223.1	760.4	.282	.221	618.5
169.0	117.8	803.2	223.0	758.1	.277	.216	615.7
170.0	117.7	805.3	223.0	755.7	.272	.211	612.8
171.0	117.7	807.4	222.9	753.4	.268	.205	609.8
172.0	117.7	809.5	222.8	751.1	.263	.200	606.7
173.0	117.7	811.6	222.8	748.8	.258	.195	603.5
174.0	117.6	813.7	222.7	746.5	.253	.190	600.3
175.0	117.6	815.8	222.6	744.1	.249	.184	597.0
176.0	117.6	817.9	222.6	741.8	.244	.179	593.5
177.0	117.6	820.0	222.5	739.5	.239	.174	590.1
178.0	117.5	822.1	222.4	737.2	.235	.169	586.5
179.0	117.5	824.2	222.3	734.8	.230	.164	582.8
180.0	117.5	826.3	222.2	732.5	.225	.159	579.0
181.0	117.4	828.4	222.2	730.1	.221	.154	575.1
182.0	117.4	830.6	222.1	727.7	.216	.149	571.1
183.0	117.4	832.7	222.0	725.4	.212	.144	567.0
184.0	117.4	834.9	221.9	723.0	.207	.139	562.8
185.0	117.3	837.0	221.8	720.6	.203	.135	558.5
186.0	117.3	839.2	221.7	718.1	.199	.130	554.1
187.0	117.3	841.4	221.6	715.7	.194	.125	549.5
188.0	117.2	843.7	221.5	713.2	.190	.120	544.8
189.0	117.2	845.9	221.4	710.8	.186	.116	540.0
190.0	117.1	848.2	221.3	708.2	.182	.111	535.0
191.0	117.1	850.5	221.2	705.7	.177	.106	529.9
192.0	117.1	852.8	221.1	703.2	.173	.102	524.6
193.0	117.0	855.1	220.9	700.6	.169	.097	519.2
194.0	117.0	857.5	220.8	697.9	.165	.093	513.6
195.0	116.9	859.8	220.7	695.3	.161	.089	507.8
196.0	116.9	862.3	220.6	692.6	.157	.084	501.9

197.0	116.8	864.7	220.4	689.9	.153	.080	495.8
198.0	116.8	867.2	220.3	687.1	.149	.076	489.4
199.0	116.8	869.7	220.1	684.3	.145	.072	482.8
200.0	116.7	872.3	220.0	681.5	.142	.068	476.0
201.0	116.6	874.9	219.8	678.6	.138	.064	468.9
202.0	116.6	877.6	219.7	675.7	.134	.060	461.5
203.0	116.5	880.3	219.5	672.7	.131	.056	454.0
204.0	116.5	883.0	219.3	669.6	.127	.052	446.0
205.0	116.4	885.8	219.1	666.5	.124	.048	437.8
206.0	116.3	888.7	218.9	663.4	.120	.045	429.1
207.0	116.3	891.6	218.7	660.1	.117	.041	420.1
208.0	116.2	894.6	218.5	656.8	.114	.038	411.0
209.0	116.4	897.6	219.2	653.4	.111	.034	412.5
210.0	116.3	900.8	218.7	649.9	.107	.030	426.3
211.0	116.2	904.0	218.5	646.3	.104	.027	411.8
212.0	116.1	907.4	218.2	642.6	.101	.024	398.9
213.0	116.0	910.9	218.0	638.8	.098	.020	390.8
214.0	115.9	914.4	217.7	634.8	.095	.017	379.7
215.0	115.8	918.2	217.3	630.6	.092	.014	363.6
216.0	115.6	922.1	216.9	626.3	.089	.011	344.8
217.0	115.4	926.1	216.4	621.8	.087	.009	324.1
218.0	115.2	930.4	215.8	617.1	.084	.006	301.0
219.0	115.0	934.9	215.1	612.1	.082	.004	274.7
220.0	114.7	939.7	214.4	606.8	.080	.003	244.0
221.0	114.4	944.8	213.4	601.1	.078	.001	207.9
222.0	115.9	950.6	212.4	594.7	.077	.000	162.4
223.0	122.2	957.3	212.2	587.3	.076	.000	136.3
224.0	128.7	963.9	212.0	580.0	.075	.000	127.1
225.0	135.2	970.5	211.9	572.7	.074	.000	120.2
226.0	141.9	976.9	211.8	565.6	.073	.000	114.9
227.0	148.6	983.3	211.7	558.5	.072	.000	110.9
228.0	155.4	989.6	211.7	551.5	.072	.000	107.6
229.0	162.4	995.7	211.6	544.7	.071	.000	105.0
230.0	169.4	1001.9	211.6	537.9	.070	.000	102.8
231.0	176.4	1007.9	211.6	531.2	.069	.000	100.9
232.0	183.6	1013.9	211.5	524.6	.068	.000	99.2
233.0	190.8	1019.7	211.5	518.1	.068	.000	97.7
234.0	198.1	1025.5	211.5	511.7	.067	.000	96.2
235.0	205.4	1031.2	211.5	505.3	.066	.000	94.9
236.0	212.9	1036.9	211.4	499.1	.065	.000	93.5
237.0	220.4	1042.5	211.4	492.9	.065	.000	92.2
238.0	227.9	1048.0	211.4	486.8	.064	.000	91.0
239.0	235.6	1053.4	211.4	480.8	.063	.000	89.7
240.0	243.2	1058.8	211.4	474.8	.062	.000	88.5
241.0	251.0	1064.1	211.3	469.0	.062	.000	87.3
242.0	258.8	1069.3	211.3	463.2	.061	.000	86.1
243.0	266.7	1074.4	211.3	457.5	.060	.000	84.9
244.0	274.6	1079.5	211.3	451.8	.060	.000	83.7
245.0	282.6	1084.5	211.3	446.3	.059	.000	82.5
246.0	290.7	1089.5	211.3	440.8	.058	.000	81.3
247.0	298.8	1094.4	211.2	435.3	.058	.000	80.1

248.0	306.9	1099.2	211.2	430.0	.057	.000	78.9
249.0	315.2	1104.0	211.2	424.7	.057	.000	77.8
250.0	323.4	1108.7	211.2	419.5	.056	.000	76.6
251.0	331.8	1113.4	211.2	414.3	.055	.000	75.5
252.0	340.1	1118.0	211.1	409.2	.055	.000	74.3
253.0	348.5	1122.5	211.1	404.2	.054	.000	73.2
254.0	357.0	1127.0	211.1	399.2	.054	.000	72.1
255.0	365.5	1131.4	211.1	394.3	.053	.000	71.0
256.0	374.1	1135.8	211.0	389.5	.052	.000	69.9
257.0	382.7	1140.1	211.0	384.7	.052	.000	68.8
258.0	391.3	1144.3	211.0	380.0	.051	.000	67.7
259.0	400.0	1148.5	211.0	375.3	.051	.000	66.6
260.0	408.7	1152.7	211.0	370.7	.050	.000	65.5
261.0	417.4	1156.8	210.9	366.2	.050	.000	64.5
262.0	426.2	1160.8	210.9	361.7	.049	.000	63.4
263.0	435.0	1164.8	210.9	357.3	.049	.000	62.4
264.0	443.8	1168.8	210.9	352.9	.048	.000	61.4
265.0	452.7	1172.7	210.9	348.6	.048	.000	60.4
266.0	461.6	1176.5	210.8	344.3	.047	.000	59.4
267.0	470.5	1180.3	210.8	340.1	.047	.000	58.4
268.0	479.4	1184.1	210.8	335.9	.047	.000	57.4
269.0	488.4	1187.8	210.8	331.8	.046	.000	56.5
270.0	497.4	1191.4	210.8	327.8	.046	.000	55.5
271.0	506.4	1195.1	210.7	323.8	.045	.000	54.6
272.0	515.4	1198.6	210.7	319.8	.045	.000	53.6
273.0	524.4	1202.2	210.7	315.9	.044	.000	52.7
274.0	533.4	1205.7	210.7	312.0	.044	.000	51.8
275.0	542.4	1209.1	210.7	308.2	.044	.000	50.9
276.0	551.5	1212.5	210.6	304.4	.043	.000	50.0
277.0	560.5	1215.9	210.6	300.7	.043	.000	49.2
278.0	569.6	1219.2	210.6	297.0	.042	.000	48.3
279.0	578.6	1222.5	210.6	293.4	.042	.000	47.5
280.0	587.7	1225.7	210.6	289.8	.042	.000	46.6
281.0	596.7	1228.9	210.5	286.2	.041	.000	45.8
282.0	605.8	1232.1	210.5	282.7	.041	.000	45.0
283.0	614.8	1235.2	210.5	279.3	.041	.000	44.2
284.0	623.8	1238.3	210.5	275.9	.040	.000	43.4
285.0	632.8	1241.3	210.5	272.5	.040	.000	42.6
286.0	641.8	1244.4	210.4	269.1	.040	.000	41.9
287.0	650.8	1247.3	210.4	265.8	.039	.000	41.1
288.0	659.8	1250.3	210.4	262.6	.039	.000	40.4
289.0	668.8	1253.2	210.4	259.3	.039	.000	39.6
290.0	677.7	1256.1	210.4	256.2	.038	.000	38.9
291.0	686.6	1258.9	210.3	253.0	.038	.000	38.2
292.0	695.5	1261.7	210.3	249.9	.038	.000	37.5
293.0	704.3	1264.5	210.3	246.8	.037	.000	36.8
294.0	713.2	1267.2	210.3	243.8	.037	.000	36.1
295.0	721.9	1269.9	210.3	240.8	.037	.000	35.5
296.0	730.7	1272.6	210.3	237.9	.037	.000	34.8
297.0	739.4	1275.2	210.2	234.9	.036	.000	34.2
298.0	748.1	1277.8	210.2	232.0	.036	.000	33.5

299.0	756.8	1280.4	210.2	229.2	.036	.000	32.9
300.0	765.4	1282.9	210.2	226.4	.036	.000	32.3



DATA ENTERED INTO AFFTAC PROGRAM FOR ANALYSIS  
Program Version 3.03, March 16, 1999

## TANK PARAMETERS

Capacity (gal): 33000.  
Inside Diameter (ins.): 119.00  
Wall Thickness (ins.): .6900  
Tank Material Type: CARBON STEEL  
Tensile Strength of Tank Material (psi): 81000.  
Nominal Burst Strength (psig): 900.0  
Calculated Burst Strength (psig): 939.3  
Tank Car Orientation with Respect  
to Vertical (deg): .00

## PRODUCT DATA

Product Thermal Property Data Contained in Program  
Product Name: PROPANE  
Product Type: Substance  
Initial Fraction of Tank Filled: .900  
Initial Temperature of Product: 60.00  
No Padding Gas Used

## SAFETY RELIEF DEVICE PARAMETERS

Safety Relief Valve Used  
Rated Flow Capacity (SCFM): 25000.  
Flow Rating Pressure (psig): 308.60  
Start-to-Discharge Pressure (psig): 280.50  
Vent or Valve Vapor Flow Discharge Coefficient: .80  
Vent or Valve Liquid Flow Discharge Coefficient: .80

## THERMAL PROTECTION SYSTEM CHARACTERISTICS

Jacketed Insulation System Not Resistant  
to High Temperature Effects  
Initial Conductance (BTU/hr-sq.ft-deg F): 4.00  
Time Interval for Linear Change from Initial Conductance  
to Final Conductance (min): .10

Discontinuities in Insulation Not Considered

No Tank Lining Used

## FIRE CONDITIONS

Standard Pool Fire Simulation Analysis  
Flame Temperature (deg F): 1500.0  
Fraction of Tank Surface Subject to Heat Input: 1.00  
Tank Radiation Emissivity Coefficient: .90



## ANALYSIS CONDITIONS

Time Limit (min): 300.00  
 Time Increment for Analysis (min): .10  
 Time Increments Between Display of Output Data: 10

THERMAL PROPERTY DATA CONTAINED IN PROGRAM  
FOR PROPANE

Temperature (degrees F), Vapor Pressure (psia), Specific Heat (BTU/lb-deg F), Specific Volume (cu. ft/lb), Heat of Vaporization (BTU/lb), Compressibility Factor of Vapor, and Ratio of Specific Heats of Vapor

Temp.	Vapor Pres.	Spec. Heat	Spec. Volume	Heat of Vap.	Vapor Comp. Fact.	Vapor Ratio of Spec. Heats
.00	38.32	.5539	.02946	170.4	.92	1.18
20.00	55.54	.5683	.03011	164.2	.90	1.21
40.00	78.78	.5855	.03076	158.0	.87	1.24
60.00	108.08	.6066	.03148	151.6	.84	1.26
80.00	144.68	.6331	.03259	143.3	.81	1.29
100.00	189.61	.6678	.03391	134.0	.77	1.37
120.00	244.39	.7236	.03549	123.2	.72	1.44
140.00	309.20	.7828	.03731	110.9	.68	1.52
160.00	386.18	.8788	.03984	95.9	.60	1.63
180.00	476.16	1.0683	.04351	75.2	.51	1.75
200.00	580.81	1.7230	.05252	35.3	.38	1.84

MOLECULAR WEIGHT: 44.00

## PRODUCT: PROPANE

TIME (min.)	TEMPERATURES (deg F)		PRESSURES		MASS FRACT. IN TANK	FILLED FRACT. OF TANK	RATE OF PRODUCT RELEASE (lbs/min)
	LIQ. PROD.	TANK VAPOR	WITHIN TANK (psi)	BURST STR. (psi)			
.0	60.0	60.0	93.4	947.3	1.000	.900	.0
1.0	62.9	105.9	97.6	947.2	1.000	.904	.0
2.0	65.9	154.1	102.9	947.0	1.000	.908	.0
3.0	69.0	201.4	108.3	946.5	1.000	.913	.0
4.0	72.0	247.6	113.9	945.4	1.000	.918	.0
5.0	75.1	292.7	119.7	943.5	1.000	.923	.0
6.0	78.2	336.6	125.7	940.7	1.000	.928	.0
7.0	81.2	379.0	131.9	936.7	1.000	.933	.0
8.0	84.3	419.9	138.2	931.4	1.000	.939	.0
9.0	87.4	459.3	144.8	924.5	1.000	.944	.0
10.0	90.5	497.0	151.7	916.1	1.000	.950	.0
11.0	93.6	533.0	158.8	906.0	1.000	.956	.0
12.0	96.8	567.1	166.2	894.4	1.000	.963	.0
13.0	99.9	599.4	173.9	881.3	1.000	.969	.0
14.0	103.1	629.9	181.9	866.8	1.000	.976	.0
15.0	106.2	658.5	190.1	851.1	1.000	.983	.0
16.0	109.4	685.1	198.7	834.6	1.000	.991	.0
17.0	112.7	709.9	207.6	817.4	1.000	.999	.0
18.0	116.1	115.8	219.2	947.2	.993	1.000	841.9
19.0	119.6	119.2	229.4	947.2	.985	1.000	1013.4
20.0	123.0	122.6	239.7	947.2	.977	1.000	1013.6
21.0	126.3	126.0	250.2	947.2	.969	1.000	1016.1
22.0	129.6	133.9	258.8	947.1	.961	.999	1061.9
23.0	130.4	181.1	262.0	946.7	.946	.984	1866.7
24.0	130.4	226.1	262.2	946.0	.928	.963	2363.0
25.0	130.4	268.7	262.0	944.6	.909	.941	2379.3
26.0	130.2	309.0	261.4	942.6	.890	.919	2371.8
27.0	130.0	347.5	260.8	939.8	.871	.897	2360.6
28.0	129.6	388.2	259.7	935.7	.853	.875	2344.2
29.0	129.3	427.2	258.6	930.3	.834	.853	2323.1
30.0	128.9	464.5	257.3	923.5	.816	.831	2300.1
31.0	128.5	500.0	256.0	915.3	.798	.809	2275.8
32.0	128.0	533.8	254.6	905.8	.781	.788	2250.7
33.0	127.6	565.9	253.2	894.8	.763	.767	2225.1
34.0	127.1	596.2	251.8	882.7	.746	.747	2199.4
35.0	126.7	624.9	250.4	869.3	.728	.726	2173.7
36.0	126.3	651.9	249.0	854.9	.711	.706	2148.4
37.0	125.8	677.2	247.6	839.7	.695	.687	2123.5
38.0	125.4	701.1	246.3	823.7	.678	.667	2099.2
39.0	125.0	723.4	245.0	807.2	.662	.648	2075.6
40.0	124.6	744.3	243.7	790.3	.645	.629	2052.7
41.0	124.2	763.9	242.5	773.1	.629	.611	2030.5
42.0	123.8	782.2	241.3	755.8	.614	.592	2009.1
43.0	123.4	799.3	240.1	738.5	.598	.574	1988.3

44.0	123.0	815.3	238.9	744.7	.582	.556	1968.3
45.0	122.7	830.2	237.8	728.2	.567	.539	1948.9
46.0	122.3	844.1	236.7	712.8	.552	.521	1930.1
47.0	122.0	857.1	235.7	698.4	.537	.504	1911.7
48.0	121.6	869.2	234.6	684.9	.522	.487	1893.8
49.0	121.3	880.6	233.6	672.3	.507	.470	1876.2
50.0	120.9	891.3	232.5	660.5	.492	.454	1858.9
51.0	120.6	901.2	231.5	649.4	.478	.438	1841.7
52.0	120.2	910.6	230.5	639.0	.463	.421	1824.5
53.0	119.9	919.4	229.4	629.3	.449	.405	1807.4
54.0	119.4	931.1	228.0	616.3	.435	.390	1788.3
55.0	118.7	944.2	226.1	601.8	.421	.374	1759.6
56.0	118.2	956.6	224.4	588.0	.407	.359	1731.0
57.0	117.8	968.3	223.3	575.1	.394	.345	1645.4
58.0	117.7	979.3	223.0	562.9	.382	.331	1567.4
59.0	117.7	989.6	222.9	551.4	.370	.318	1544.2
60.0	117.7	999.4	222.8	540.6	.357	.304	1532.5
61.0	117.6	1008.7	222.7	530.3	.345	.291	1522.3
62.0	117.6	1017.5	222.6	520.6	.333	.278	1511.5
63.0	117.6	1025.9	222.5	511.3	.322	.265	1499.7
64.0	117.5	1033.9	222.4	502.4	.310	.252	1486.7
65.0	117.5	1041.5	222.3	493.9	.298	.239	1472.7
66.0	117.4	1048.9	222.2	485.8	.287	.226	1457.7
67.0	117.4	1056.0	222.0	477.9	.275	.214	1441.5
68.0	117.3	1062.8	221.9	470.4	.264	.202	1424.1
69.0	117.3	1069.4	221.7	463.0	.253	.189	1405.5
70.0	117.2	1075.9	221.5	455.9	.242	.177	1385.7
71.0	117.2	1082.2	221.3	448.9	.231	.166	1364.7
72.0	117.1	1088.4	221.1	442.0	.221	.154	1342.5
73.0	117.0	1094.4	220.9	435.3	.210	.143	1318.8
74.0	116.9	1100.5	220.7	428.6	.200	.132	1293.6
75.0	116.9	1106.4	220.5	422.0	.190	.121	1267.0
76.0	116.8	1112.4	220.2	415.4	.180	.110	1238.8
77.0	116.7	1118.3	219.9	408.9	.171	.100	1208.8
78.0	116.6	1124.3	219.7	402.2	.161	.089	1176.9
79.0	116.5	1130.3	219.4	395.6	.152	.080	1142.6
80.0	116.4	1136.3	219.0	388.8	.144	.070	1106.4
81.0	116.2	1142.5	218.7	382.0	.135	.061	1067.3
82.0	116.1	1148.8	218.3	375.0	.127	.052	1025.3
83.0	116.0	1155.3	217.9	367.8	.119	.044	979.8
84.0	116.0	1162.0	217.3	360.4	.112	.036	931.5
85.0	116.0	1169.0	217.6	352.7	.105	.028	947.7
86.0	115.6	1176.3	216.8	344.5	.098	.021	883.6
87.0	115.4	1184.2	216.3	335.8	.091	.014	827.9
88.0	115.0	1192.7	215.3	326.4	.085	.008	735.2
89.0	114.5	1202.0	213.9	316.0	.080	.003	610.4
90.0	114.6	1212.7	212.0	304.2	.077	.000	432.7
91.0	122.6	1226.2	211.0	289.3	.075	.000	257.2
92.0	131.2	1239.0	210.6	275.1	.073	.000	184.6
93.0	140.1	1251.2	210.5	261.6	.072	.000	155.4
94.0	149.2	1262.8	210.4	248.6	.071	.000	143.3

95.0	158.6	1274.0	210.4	236.3	.070	.000	137.7
96.0	168.1	1284.6	210.4	224.5	.069	.000	134.4
97.0	177.7	1294.7	210.4	213.3	.068	.000	132.0
97.3	180.6	1297.6	210.1	210.1	.068	.000	87.1

TMID Baseline with FOS = 1.6

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction = 9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) = 15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
temperature dependent insulation properties
properties for KAOWOOL
kaowool density (kg/m^3) =      72.200000
  
```

at failure (burst pressure)/(tank pressure) = 1.600000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	184.1	2.0	570.0	60.0	.477	28522.3
.0	20.0	168.7	2.0	570.0	60.0	.510	30255.6
.0	30.0	155.0	2.0	570.0	60.0	.549	31940.2
.0	40.0	142.0	2.0	570.0	60.0	.592	34277.6
.0	50.0	127.6	2.0	570.0	60.0	.638	36335.2
.0	60.0	115.1	2.0	570.0	60.0	.677	38058.4
.0	70.0	106.7	2.0	570.0	60.0	.693	39012.3
.0	80.0	102.2	2.0	570.0	60.0	.682	38324.6
.0	90.0	98.4	2.0	570.0	60.0	.670	37881.6
.0	100.0	95.1	2.0	570.0	60.0	.659	37210.7
.0	110.0	92.2	2.0	570.0	60.0	.647	36667.8
.0	120.0	89.4	2.0	570.0	60.0	.635	36203.2
.0	130.0	86.8	2.0	570.1	60.0	.623	35845.8
.0	140.0	84.4	2.0	570.1	60.0	.611	35120.3
.0	150.0	82.2	2.0	570.0	60.0	.600	34453.5
.0	160.0	80.1	2.0	570.0	60.0	.588	33893.8



tank model with jacket.OUT

.0	170.0	78.2	2.0	570.1	60.0	.577	33394.9
.0	180.0	76.5	2.0	570.0	60.0	.566	32993.0

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)=      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.600000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	101.3	2.0	570.0	60.0	.529	31083.7
.0	20.0	97.5	2.0	570.0	60.0	.545	31935.4
.0	30.0	93.6	2.0	570.1	60.0	.564	32902.2
.0	40.0	89.4	2.0	570.1	60.0	.584	33811.7
.0	50.0	85.3	2.0	570.0	60.0	.604	34684.1
.0	60.0	81.6	2.0	570.1	60.0	.620	35615.1
.0	70.0	78.3	2.0	570.0	60.0	.631	35990.2
.0	80.0	76.5	2.0	570.0	60.0	.629	35994.2
.0	90.0	75.2	2.0	570.0	60.0	.621	35502.6
.0	100.0	74.0	2.0	570.0	60.0	.613	35518.1
.0	110.0	72.9	2.0	570.1	60.0	.605	35097.0
.0	120.0	71.8	2.0	570.1	60.0	.597	34672.8
.0	130.0	70.8	2.0	570.0	60.0	.589	34296.3
.0	140.0	69.8	2.0	570.1	60.0	.581	33945.4
.0	150.0	68.8	2.0	570.0	60.0	.574	33567.2
.0	160.0	67.9	2.0	570.0	60.0	.566	33314.4
.0	170.0	67.0	2.0	570.0	60.0	.558	32992.9
.0	180.0	66.1	2.0	570.0	60.0	.551	32108.3

TMID 0-85 deg defect, Kaowool Properties

## Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D               =      5.770000
tank volume (m^3)      =      122.357100
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      0.000000E+00
angle to defect bot (deg) =      85.000000
temperature dependent insulation properties
properties for KAOWOOL
kaowool density (kg/m^3) =      72.200000

```

time (min)	press (MPa)	pbst (MPa)	fill (C)	tlad (C)	twld (C)	twi (C)	twli (C)	twld (C)	tjvd (C)	tjvi (C)	tjld (C)	tjli (C)	mliq (kg)	mvap (kg)	mtot (kg)	mdot (kg/s)	kins (W/mK)	qdottot (kW)
1.0	.7	6.4	.900	16.	19.	17.	17.	16.	394.	407.	394.	407.	55703.	197.	55900.	.0	.071	282.
2.0	.7	6.4	.901	16.	37.	21.	21.	17.	591.	658.	591.	658.	55700.	197.	55897.	.0	.122	977.
3.0	.7	6.4	.902	17.	67.	28.	23.	18.	642.	751.	641.	750.	55695.	197.	55893.	.0	.144	1405.
4.0	.7	6.4	.903	17.	99.	36.	24.	19.	652.	774.	651.	774.	55695.	197.	55892.	.0	.150	1531.

tank model with jacket.OUT

5.0	.7	6.4	.905	18.	131.	45.	25.	20.	655.	780.	652.	779.	55689.	198.	55886.	.0	.151	1571.
6.0	.7	6.4	.907	19.	163.	53.	25.	20.	656.	782.	653.	781.	55685.	197.	55882.	.0	.152	1593.
7.0	.7	6.3	.908	19.	194.	61.	26.	21.	658.	782.	653.	781.	55677.	197.	55874.	.0	.152	1608.
8.0	.7	6.3	.910	20.	225.	70.	27.	21.	660.	782.	653.	781.	55667.	197.	55864.	.0	.152	1626.
9.0	.8	6.2	.912	21.	254.	78.	27.	22.	662.	783.	653.	781.	55664.	196.	55861.	.0	.152	1642.
10.0	.8	6.1	.913	21.	282.	86.	28.	23.	665.	783.	653.	781.	55658.	196.	55854.	.0	.152	1665.
11.0	.8	6.0	.915	22.	308.	94.	29.	23.	667.	783.	653.	781.	55647.	195.	55843.	.0	.153	1685.
12.0	.8	5.9	.917	22.	333.	102.	29.	24.	670.	784.	653.	781.	55641.	194.	55835.	.0	.153	1707.
13.0	.8	5.7	.918	23.	357.	110.	30.	25.	674.	784.	653.	781.	55636.	193.	55829.	.0	.154	1732.
14.0	.8	5.5	.921	24.	379.	118.	31.	25.	677.	784.	653.	781.	55650.	191.	55841.	.0	.154	1753.
15.0	.8	5.3	.923	25.	399.	126.	31.	26.	680.	784.	653.	781.	55659.	189.	55849.	.0	.155	1779.
16.0	.9	5.1	.925	25.	418.	134.	32.	27.	683.	784.	653.	781.	55664.	188.	55851.	.0	.155	1809.
critical wall temperature reached																		
17.0	.9	5.1	.927	26.	435.	142.	33.	28.	687.	785.	653.	781.	55663.	185.	55848.	.0	.156	1834.
18.0	.9	4.8	.929	27.	450.	150.	33.	28.	690.	785.	653.	781.	55657.	183.	55840.	.0	.156	1856.
19.0	.9	4.7	.932	27.	464.	158.	34.	29.	693.	785.	653.	781.	55646.	181.	55827.	.0	.157	1883.
20.0	.9	4.5	.934	28.	476.	166.	35.	30.	696.	785.	653.	781.	55642.	178.	55821.	.0	.157	1902.
21.0	1.0	4.3	.936	29.	487.	174.	36.	31.	698.	785.	653.	781.	55635.	176.	55810.	.0	.157	1926.
22.0	1.0	4.2	.938	30.	497.	181.	36.	31.	700.	786.	653.	781.	55624.	173.	55797.	.0	.158	1946.
23.0	1.0	4.1	.940	30.	506.	189.	37.	32.	703.	786.	653.	781.	55610.	170.	55784.	.0	.158	1965.
24.0	1.0	4.0	.943	31.	513.	196.	38.	33.	705.	786.	653.	781.	55610.	166.	55777.	.0	.159	1980.
25.0	1.0	3.9	.945	32.	520.	203.	39.	34.	706.	786.	653.	781.	55603.	163.	55766.	.0	.159	2001.
26.0	1.1	3.8	.947	33.	525.	210.	39.	34.	708.	786.	653.	781.	55592.	159.	55751.	.0	.160	2013.
27.0	1.1	3.8	.949	34.	530.	217.	40.	35.	709.	787.	653.	781.	55579.	155.	55734.	.0	.160	2031.
28.0	1.1	3.7	.952	34.	535.	224.	41.	36.	710.	787.	653.	781.	55592.	149.	55741.	.0	.161	2037.
29.0	1.1	3.7	.956	35.	538.	230.	42.	37.	712.	787.	653.	781.	55615.	141.	55757.	.0	.161	2054.
30.0	1.1	3.6	.959	36.	541.	236.	43.	38.	712.	787.	653.	781.	55635.	134.	55769.	.0	.161	2070.
31.0	1.2	3.6	.962	37.	544.	242.	44.	38.	713.	787.	653.	781.	55652.	126.	55778.	.0	.162	2085.
32.0	1.2	3.5	.966	38.	547.	248.	44.	39.	714.	788.	653.	781.	55672.	117.	55789.	.0	.162	2099.
33.0	1.2	3.5	.969	39.	549.	254.	45.	40.	715.	788.	653.	782.	55689.	108.	55796.	.0	.163	2115.
34.0	1.2	3.5	.972	39.	550.	259.	46.	41.	715.	788.	653.	782.	55702.	98.	55801.	.0	.163	2129.
35.0	1.3	3.5	.975	40.	552.	264.	47.	42.	715.	788.	653.	782.	55713.	89.	55802.	.0	.163	2141.
36.0	1.3	3.5	.979	41.	553.	269.	48.	43.	716.	788.	653.	782.	55723.	79.	55801.	.0	.164	2152.
37.0	1.3	3.4	.982	42.	554.	274.	49.	43.	716.	788.	653.	782.	55731.	67.	55799.	.0	.164	2171.
38.0	1.4	3.4	.985	43.	555.	278.	49.	44.	716.	789.	653.	782.	55737.	56.	55793.	.0	.164	2189.
39.0	1.4	3.4	.989	44.	556.	282.	50.	45.	717.	789.	653.	782.	55738.	45.	55783.	.0	.164	2206.
40.0	1.4	3.4	.992	44.	556.	286.	51.	46.	717.	789.	653.	782.	55736.	33.	55769.	.0	.165	2230.
41.0	1.4	3.4	.995	45.	557.	290.	52.	47.	717.	789.	653.	782.	55730.	20.	55750.	.0	.165	2253.
42.0	1.5	6.0	.999	46.	285.	161.	53.	48.	709.	789.	653.	782.	55732.	6.	55738.	.0	.158	2346.

43.0	1.5	6.41.000	47.	55.	49.	54.	49.	662.	784.	653.	782.	55607.	0.	55607.	3.3	.152	2350.
44.0	1.5	6.41.000	48.	55.	49.	55.	49.	655.	782.	653.	782.	55408.	0.	55408.	3.3	.152	2349.
45.0	1.6	6.41.000	49.	55.	50.	55.	50.	653.	782.	653.	782.	55199.	0.	55199.	3.6	.152	2349.
46.0	1.6	6.41.000	50.	56.	51.	56.	51.	653.	782.	653.	782.	54982.	0.	54982.	3.6	.152	2348.
47.0	1.6	6.41.000	51.	57.	52.	57.	52.	653.	782.	653.	782.	54766.	0.	54766.	3.6	.152	2347.
48.0	1.7	6.41.000	51.	58.	53.	58.	53.	653.	782.	653.	782.	54552.	0.	54552.	3.6	.152	2346.
49.0	1.7	6.41.000	52.	59.	54.	59.	54.	653.	782.	653.	782.	54336.	0.	54336.	3.7	.152	2344.
50.0	1.7	6.41.000	53.	60.	55.	60.	55.	653.	782.	653.	782.	54114.	0.	54114.	3.7	.152	2343.
51.0	1.8	6.41.000	54.	61.	56.	61.	56.	653.	782.	653.	782.	53893.	0.	53893.	3.7	.153	2341.
52.0	1.8	6.41.000	55.	61.	56.	62.	56.	653.	782.	653.	782.	53673.	0.	53673.	3.7	.153	2339.
53.0	1.8	6.41.000	56.	62.	57.	62.	57.	653.	782.	653.	782.	53454.	0.	53454.	3.6	.153	2338.
54.0	1.9	6.41.000	57.	63.	58.	63.	58.	653.	782.	653.	782.	53218.	0.	53218.	4.0	.153	2337.
55.0	1.9	6.41.000	58.	64.	59.	64.	59.	653.	782.	653.	782.	52982.	0.	52982.	4.0	.153	2335.
56.0	1.9	6.41.000	58.	65.	60.	65.	60.	653.	782.	653.	782.	52742.	0.	52742.	4.0	.153	2329.
57.0	2.0	6.41.000	59.	66.	61.	66.	61.	654.	782.	654.	782.	52503.	0.	52503.	4.0	.153	2328.
58.0	2.0	6.4 .997	60.	69.	62.	67.	62.	654.	782.	654.	782.	52185.	15.	52200.	8.4	.153	2260.
59.0	2.0	6.4 .988	60.	103.	71.	67.	62.	654.	783.	654.	782.	51705.	68.	51773.	7.7	.153	2088.
60.0	2.0	6.4 .979	60.	135.	79.	67.	62.	655.	783.	654.	782.	51253.	117.	51370.	7.4	.153	1996.
61.0	2.0	6.4 .971	60.	167.	87.	67.	62.	657.	783.	654.	782.	50816.	165.	50982.	7.2	.153	1937.
62.0	2.0	6.3 .963	60.	199.	95.	67.	62.	658.	783.	654.	782.	50391.	212.	50603.	7.0	.154	1892.
63.0	2.0	6.3 .955	60.	229.	103.	67.	62.	660.	784.	654.	782.	49974.	258.	50232.	6.9	.154	1850.
64.0	2.0	6.2 .947	60.	258.	110.	67.	62.	663.	784.	654.	782.	49565.	303.	49867.	6.8	.154	1826.
65.0	2.0	6.1 .939	60.	286.	118.	67.	62.	665.	784.	654.	782.	49160.	347.	49507.	6.7	.155	1811.
66.0	2.0	6.0 .932	60.	313.	126.	67.	62.	668.	784.	654.	782.	48759.	391.	49150.	6.7	.155	1799.
67.0	2.0	5.8 .924	60.	338.	134.	67.	62.	671.	784.	654.	782.	48360.	435.	48795.	6.6	.156	1786.
68.0	2.0	5.7 .917	60.	361.	141.	67.	62.	674.	785.	654.	782.	47963.	478.	48441.	6.6	.156	1782.
69.0	2.0	5.5 .909	60.	383.	149.	67.	62.	677.	785.	654.	782.	47567.	522.	48089.	6.6	.157	1776.
70.0	2.0	5.3 .901	60.	403.	157.	67.	62.	681.	785.	654.	782.	47172.	565.	47737.	6.6	.157	1779.
71.0	2.0	5.1 .894	60.	422.	165.	67.	62.	684.	785.	654.	782.	46776.	608.	47384.	6.6	.158	1782.
72.0	2.0	5.0 .886	60.	439.	173.	67.	62.	687.	785.	654.	782.	46379.	652.	47031.	6.6	.158	1786.
73.0	2.0	4.8 .879	60.	454.	180.	67.	62.	691.	786.	654.	782.	45982.	695.	46677.	6.6	.159	1788.
74.0	2.0	4.6 .871	60.	468.	188.	67.	62.	694.	786.	654.	782.	45583.	739.	46322.	6.7	.159	1795.
75.0	2.0	4.4 .863	60.	480.	196.	67.	62.	696.	786.	654.	782.	45183.	783.	45966.	6.7	.159	1799.
76.0	2.0	4.3 .856	60.	491.	204.	67.	62.	699.	786.	654.	782.	44782.	827.	45609.	6.7	.160	1805.
77.0	2.0	4.2 .848	60.	501.	211.	67.	62.	701.	786.	654.	782.	44381.	871.	45251.	6.7	.160	1808.
78.0	2.0	4.0 .840	60.	510.	219.	67.	62.	704.	787.	654.	782.	43978.	915.	44893.	6.7	.161	1813.
79.0	2.0	3.9 .833	60.	517.	227.	67.	62.	706.	787.	654.	782.	43574.	959.	44533.	6.7	.161	1816.
80.0	2.0	3.8 .825	60.	524.	234.	67.	62.	707.	787.	654.	782.	43170.	1004.	44173.	6.7	.162	1819.
81.0	2.0	3.8 .817	60.	530.	242.	67.	62.	709.	787.	654.	782.	42765.	1048.	43813.	6.7	.162	1821.



tank model with jacket.OUT

82.0	2.0	3.7	.809	60.	535.	249.	67.	62.	710.	788.	654.	782.	42359.	1092.	43452.	6.8	.163	1824.
83.0	2.0	3.6	.802	60.	539.	256.	67.	62.	712.	788.	654.	782.	41954.	1137.	43091.	6.8	.163	1824.
84.0	2.0	3.6	.794	60.	543.	263.	67.	62.	713.	788.	654.	782.	41548.	1181.	42730.	6.8	.164	1823.
85.0	2.0	3.5	.786	60.	547.	271.	67.	62.	714.	788.	654.	782.	41143.	1226.	42368.	6.8	.164	1824.
86.0	2.0	3.5	.778	60.	550.	277.	67.	62.	715.	789.	654.	782.	40737.	1270.	42007.	6.8	.164	1821.
87.0	2.0	3.5	.771	60.	552.	284.	67.	62.	716.	789.	654.	782.	40332.	1315.	41647.	6.7	.165	1821.
88.0	2.0	3.4	.763	60.	555.	291.	67.	62.	716.	789.	654.	782.	39927.	1359.	41286.	6.7	.165	1820.
89.0	2.0	3.4	.755	60.	557.	297.	67.	62.	717.	789.	654.	782.	39523.	1403.	40926.	6.7	.166	1818.
90.0	2.0	3.4	.747	60.	559.	304.	67.	62.	717.	789.	654.	782.	39119.	1448.	40567.	6.7	.166	1813.
91.0	2.0	3.4	.740	60.	560.	310.	67.	62.	718.	790.	654.	782.	38716.	1492.	40208.	6.7	.167	1811.
92.0	2.0	3.3	.732	60.	562.	316.	67.	62.	718.	790.	654.	782.	38313.	1536.	39849.	6.7	.167	1808.
93.0	2.0	3.3	.724	60.	563.	322.	67.	62.	719.	790.	654.	782.	37911.	1580.	39491.	6.7	.167	1805.
94.0	2.0	3.3	.717	60.	565.	327.	67.	62.	719.	790.	654.	782.	37510.	1624.	39134.	6.7	.168	1802.
95.0	2.0	3.3	.709	60.	566.	333.	67.	62.	719.	790.	654.	782.	37110.	1668.	38778.	6.7	.168	1798.
96.0	2.0	3.3	.701	60.	567.	338.	67.	62.	720.	791.	654.	782.	36710.	1712.	38422.	6.7	.169	1795.
97.0	2.0	3.3	.694	60.	568.	344.	67.	62.	720.	791.	654.	782.	36311.	1756.	38067.	6.6	.169	1792.
98.0	2.0	3.2	.686	60.	569.	349.	67.	62.	720.	791.	654.	782.	35913.	1799.	37712.	6.6	.169	1788.
99.0	2.0	3.2	.679	60.	570.	354.	67.	62.	721.	791.	654.	782.	35516.	1843.	37359.	6.6	.170	1783.
100.0	2.0	3.2	.671	60.	570.	358.	67.	62.	721.	791.	654.	782.	35120.	1886.	37006.	6.6	.170	1780.
101.0	2.0	3.2	.664	60.	571.	363.	67.	62.	721.	792.	654.	782.	34724.	1929.	36654.	6.6	.171	1775.
AFTAC model with fos = 1.600000								62.	721.	792.	654.	782.	34540.	1950.	36654.	6.6	.171	1773.
101.5	2.0	3.2	.660	60.	572.	365.	67.	62.	721.	792.	654.	782.	34330.	1973.	36303.	6.6	.171	1770.
102.0	2.0	3.2	.656	60.	572.	367.	67.	62.	721.	792.	654.	782.	33937.	2016.	35953.	6.5	.171	1767.
103.0	2.0	3.2	.648	60.	573.	372.	67.	62.	722.	792.	654.	782.	33544.	2059.	35603.	6.5	.172	1762.
104.0	2.0	3.2	.641	60.	573.	376.	67.	62.	722.	792.	654.	782.	33153.	2102.	35255.	6.5	.172	1758.
105.0	2.0	3.2	.633	60.	574.	380.	67.	62.	722.	792.	654.	782.	32762.	2145.	34907.	6.5	.172	1753.
106.0	2.0	3.2	.626	60.	575.	384.	67.	62.	722.	792.	654.	782.	32373.	2187.	34560.	6.5	.172	1749.
107.0	2.0	3.1	.619	60.	576.	388.	67.	62.	722.	792.	654.	782.	31985.	2230.	34215.	6.5	.173	1743.
108.0	2.0	3.1	.611	60.	576.	391.	67.	62.	723.	793.	654.	782.	31598.	2272.	33870.	6.4	.173	1738.
109.0	2.0	3.1	.604	60.	577.	395.	67.	62.	723.	793.	654.	782.	31212.	2315.	33526.	6.4	.173	1733.
110.0	2.0	3.1	.596	60.	578.	398.	67.	62.	723.	793.	654.	782.	30827.	2357.	33184.	6.4	.174	1728.
111.0	2.0	3.1	.589	60.	578.	401.	67.	62.	723.	793.	654.	782.	30443.	2399.	32842.	6.4	.174	1723.
112.0	2.0	3.1	.582	60.	579.	405.	67.	62.	724.	793.	654.	782.	30060.	2441.	32501.	6.4	.174	1717.
113.0	2.0	3.1	.574	60.	579.	408.	67.	62.	724.	793.	654.	782.	29679.	2483.	32162.	6.3	.174	1712.
114.0	2.0	3.1	.567	60.	580.	411.	67.	62.	724.	793.	654.	782.	29299.	2524.	31823.	6.3	.175	1706.
115.0	2.0	3.1	.560	60.	581.	414.	67.	62.	724.	794.	653.	782.	28920.	2566.	31486.	6.3	.175	1701.
116.0	2.0	3.1	.553	60.	581.	416.	62.	62.	724.	794.	653.	782.	28542.	2607.	31149.	6.3	.175	1701.
117.0	2.0	3.1	.545	60.	582.	419.	62.	62.	724.	794.	653.	782.	28164.	2649.	30812.	6.3	.175	1700.
118.0	2.0	3.1	.538	60.	583.	422.	62.	62.	725.	794.	653.	782.	28164.	2649.	30812.	6.3	.175	1700.

119.0	2.0	3.0	.531	60.	583.	424.	62.	725.	794.	653.	782.	27786.	2690.	30476.	6.3	.175	1698.
120.0	2.0	3.0	.524	60.	584.	427.	62.	725.	794.	653.	782.	27408.	2732.	30140.	6.3	.176	1697.
121.0	2.0	3.0	.516	60.	584.	429.	62.	725.	794.	653.	782.	27031.	2773.	29804.	6.3	.176	1696.
122.0	2.0	3.0	.509	60.	585.	431.	62.	725.	794.	653.	782.	26654.	2814.	29468.	6.3	.176	1694.
123.0	2.0	3.0	.502	60.	585.	433.	62.	725.	794.	653.	782.	26277.	2856.	29133.	6.3	.176	1691.
124.0	2.0	3.0	.495	60.	586.	435.	62.	725.	794.	653.	782.	25901.	2897.	28798.	6.3	.176	1689.
125.0	2.0	3.0	.488	60.	586.	437.	62.	726.	794.	653.	782.	25526.	2938.	28464.	6.3	.177	1687.
126.0	2.0	3.0	.481	60.	587.	439.	62.	726.	794.	653.	782.	25151.	2979.	28130.	6.2	.177	1684.
127.0	2.0	3.0	.473	60.	587.	441.	62.	726.	795.	653.	782.	24777.	3020.	27797.	6.2	.177	1682.
128.0	2.0	3.0	.466	60.	588.	443.	62.	726.	795.	653.	782.	24403.	3061.	27464.	6.2	.177	1679.
129.0	2.0	3.0	.459	60.	588.	444.	62.	726.	795.	653.	782.	24030.	3102.	27132.	6.2	.177	1676.
130.0	2.0	3.0	.452	60.	589.	446.	62.	726.	795.	653.	782.	23657.	3143.	26800.	6.2	.178	1673.
131.0	2.0	3.0	.445	60.	589.	448.	62.	726.	795.	653.	782.	23286.	3184.	26469.	6.2	.178	1670.
132.0	2.0	3.0	.438	60.	589.	449.	62.	727.	795.	653.	782.	22915.	3224.	26139.	6.2	.178	1665.
133.0	2.0	3.0	.431	60.	590.	451.	62.	727.	795.	653.	782.	22545.	3265.	25809.	6.2	.178	1662.
134.0	2.0	2.9	.424	60.	590.	452.	62.	727.	795.	653.	782.	22175.	3305.	25481.	6.1	.178	1658.
135.0	2.0	2.9	.417	60.	591.	454.	62.	727.	795.	653.	782.	21807.	3346.	25152.	6.1	.178	1655.
136.0	2.0	2.9	.410	60.	591.	455.	62.	727.	795.	653.	782.	21439.	3386.	24825.	6.1	.179	1651.
137.0	2.0	2.9	.403	60.	592.	457.	62.	727.	795.	653.	782.	21073.	3426.	24499.	6.1	.179	1646.
138.0	2.0	2.9	.396	60.	592.	458.	62.	727.	795.	653.	782.	20707.	3466.	24173.	6.1	.179	1642.
139.0	2.0	2.9	.389	60.	593.	460.	62.	728.	795.	653.	782.	20342.	3506.	23848.	6.1	.179	1638.
140.0	2.0	2.9	.382	60.	593.	461.	62.	728.	795.	653.	782.	19978.	3546.	23524.	6.1	.179	1633.
141.0	2.0	2.9	.375	60.	594.	462.	62.	728.	795.	653.	782.	19615.	3586.	23201.	6.0	.179	1628.
142.0	2.0	2.9	.368	60.	594.	464.	62.	728.	795.	653.	782.	19254.	3626.	22879.	6.0	.180	1624.
143.0	2.0	2.9	.361	60.	594.	465.	62.	728.	795.	653.	782.	18893.	3665.	22558.	6.0	.180	1619.
144.0	2.0	2.9	.354	60.	595.	467.	62.	728.	796.	653.	782.	18533.	3704.	22238.	6.0	.180	1614.
145.0	2.0	2.9	.347	60.	595.	468.	62.	728.	796.	653.	782.	18175.	3744.	21919.	6.0	.180	1609.
146.0	2.0	2.9	.340	60.	596.	469.	62.	729.	796.	653.	782.	17818.	3783.	21601.	5.9	.180	1604.
147.0	2.0	2.9	.334	60.	596.	470.	62.	729.	796.	653.	782.	17462.	3822.	21284.	5.9	.180	1598.
148.0	2.0	2.9	.327	60.	597.	472.	62.	729.	796.	653.	782.	17107.	3861.	20968.	5.9	.180	1593.
149.0	2.0	2.9	.320	60.	597.	473.	62.	729.	796.	653.	782.	16753.	3900.	20653.	5.9	.181	1587.
150.0	2.0	2.8	.313	60.	598.	474.	62.	729.	796.	653.	782.	16401.	3938.	20339.	5.9	.181	1581.
151.0	2.0	2.8	.307	60.	598.	476.	62.	729.	796.	653.	782.	16049.	3977.	20026.	5.8	.181	1576.
152.0	2.0	2.8	.300	60.	599.	477.	62.	730.	796.	653.	782.	15700.	4015.	19715.	5.8	.181	1570.
153.0	2.0	2.8	.293	60.	599.	478.	62.	730.	796.	653.	782.	15351.	4053.	19405.	5.8	.181	1563.
154.0	2.0	2.8	.287	60.	600.	480.	62.	730.	796.	653.	782.	15004.	4091.	19095.	5.8	.181	1557.
155.0	2.0	2.8	.280	60.	601.	481.	62.	730.	796.	653.	782.	14658.	4129.	18788.	5.7	.181	1551.
156.0	2.0	2.8	.273	60.	601.	482.	62.	730.	796.	653.	782.	14314.	4167.	18481.	5.7	.181	1544.
157.0	2.0	2.8	.267	60.	602.	483.	62.	730.	796.	653.	782.	13971.	4205.	18176.	5.7	.182	1537.

158.0	2.0	2.8	2.0	260	60.	602.	485.	62.	62.	731.	796.	653.	782.	13630.	4242.	17872.	5.7	.182	1531.
159.0	2.0	2.8	2.0	254	60.	603.	486.	62.	62.	731.	796.	653.	782.	13290.	4279.	17570.	5.6	.182	1524.
160.0	2.0	2.8	2.0	247	60.	603.	487.	62.	62.	731.	796.	653.	782.	12952.	4316.	17269.	5.6	.182	1517.
161.0	2.0	2.8	2.0	241	60.	604.	489.	62.	62.	731.	796.	653.	782.	12616.	4353.	16969.	5.6	.182	1509.
162.0	2.0	2.8	2.0	235	60.	604.	490.	62.	62.	731.	797.	653.	782.	12281.	4390.	16671.	5.6	.182	1502.
163.0	2.0	2.7	2.0	228	60.	605.	492.	62.	62.	732.	797.	653.	782.	11947.	4427.	16374.	5.5	.182	1494.
164.0	2.0	2.7	2.0	222	60.	606.	493.	62.	62.	732.	797.	653.	782.	11616.	4463.	16079.	5.5	.183	1487.
165.0	2.0	2.7	2.0	216	60.	606.	494.	62.	62.	732.	797.	653.	782.	11286.	4499.	15785.	5.5	.183	1479.
166.0	2.0	2.7	2.0	209	60.	607.	496.	62.	62.	732.	797.	653.	782.	10958.	4535.	15493.	5.5	.183	1470.
167.0	2.0	2.7	2.0	203	60.	608.	497.	62.	62.	732.	797.	653.	782.	10632.	4571.	15203.	5.4	.183	1462.
168.0	2.0	2.7	2.0	197	60.	608.	499.	62.	62.	733.	797.	653.	782.	10308.	4606.	14914.	5.4	.183	1453.
169.0	2.0	2.7	2.0	191	60.	609.	500.	62.	62.	733.	797.	653.	782.	9986.	4642.	14627.	5.4	.183	1445.
170.0	2.0	2.7	2.0	185	60.	610.	502.	62.	62.	733.	797.	653.	782.	9665.	4677.	14342.	5.3	.184	1436.
171.0	2.0	2.7	2.0	179	60.	610.	503.	62.	62.	733.	797.	653.	782.	9347.	4712.	14059.	5.3	.184	1426.
172.0	2.0	2.7	2.0	172	60.	611.	505.	62.	62.	733.	797.	653.	782.	9031.	4746.	13777.	5.3	.184	1417.
173.0	2.0	2.7	2.0	166	60.	612.	506.	62.	62.	734.	797.	653.	782.	8717.	4781.	13497.	5.2	.184	1406.
174.0	2.0	2.6	2.0	161	60.	613.	508.	62.	62.	734.	797.	653.	782.	8405.	4815.	13220.	5.2	.184	1397.
175.0	2.0	2.6	2.0	155	60.	613.	509.	62.	62.	734.	797.	653.	782.	8095.	4849.	12944.	5.1	.184	1386.
176.0	2.0	2.6	2.0	149	60.	614.	511.	62.	62.	734.	797.	653.	782.	7788.	4882.	12671.	5.1	.185	1375.
177.0	2.0	2.6	2.0	143	60.	615.	512.	62.	62.	735.	797.	653.	782.	7484.	4916.	12399.	5.1	.185	1365.
178.0	2.0	2.6	2.0	137	60.	616.	514.	62.	62.	735.	798.	653.	782.	7181.	4949.	12130.	5.0	.185	1354.
179.0	2.0	2.6	2.0	131	60.	617.	516.	62.	62.	735.	798.	653.	782.	6882.	4982.	11863.	5.0	.185	1342.
180.0	2.0	2.6	2.0	126	60.	618.	518.	62.	62.	736.	798.	653.	782.	6585.	5014.	11599.	4.9	.185	1329.
181.0	2.0	2.6	2.0	120	60.	618.	519.	62.	62.	736.	798.	653.	782.	6290.	5047.	11337.	4.9	.185	1316.
182.0	2.0	2.6	2.0	115	60.	619.	521.	62.	62.	736.	798.	653.	782.	5999.	5079.	11077.	4.8	.186	1304.
183.0	2.0	2.5	2.0	109	60.	620.	523.	62.	62.	736.	798.	653.	782.	5710.	5110.	10821.	4.8	.186	1290.
184.0	2.0	2.5	2.0	104	60.	621.	525.	62.	62.	737.	798.	653.	782.	5425.	5142.	10566.	4.7	.186	1276.
185.0	2.0	2.5	2.0	98	60.	622.	527.	62.	62.	737.	798.	653.	782.	5143.	5173.	10315.	4.7	.186	1261.
186.0	2.0	2.5	2.0	93	60.	623.	529.	62.	62.	737.	798.	653.	782.	4864.	5203.	10067.	4.6	.186	1247.
187.0	2.0	2.5	2.0	88	60.	624.	531.	62.	62.	738.	798.	653.	782.	4588.	5233.	9821.	4.6	.187	1230.
188.0	2.0	2.5	2.0	82	60.	626.	533.	62.	62.	738.	798.	653.	782.	4316.	5263.	9579.	4.5	.187	1214.
189.0	2.0	2.5	2.0	77	60.	627.	535.	62.	62.	739.	798.	653.	782.	4048.	5293.	9341.	4.4	.187	1197.
190.0	2.0	2.4	2.0	72	60.	628.	537.	62.	62.	739.	799.	653.	782.	3784.	5321.	9105.	4.4	.187	1179.
191.0	2.0	2.4	2.0	67	60.	629.	539.	62.	62.	739.	799.	653.	782.	3524.	5350.	8874.	4.3	.188	1160.
192.0	2.0	2.4	2.0	62	60.	630.	541.	62.	62.	740.	799.	653.	782.	3268.	5378.	8646.	4.2	.188	1140.
193.0	2.0	2.4	2.0	58	60.	632.	544.	62.	62.	740.	799.	653.	782.	3017.	5406.	8422.	4.1	.188	1118.
194.0	2.0	2.4	2.0	53	60.	633.	546.	62.	62.	741.	799.	653.	782.	2770.	5433.	8203.	4.1	.188	1096.
195.0	2.0	2.4	2.0	48	60.	634.	548.	62.	62.	741.	799.	653.	782.	2529.	5459.	7988.	4.0	.189	1073.
196.0	2.0	2.3	2.0	44	60.	636.	551.	62.	62.	742.	799.	653.	782.	2293.	5485.	7778.	3.9	.189	1047.

tank model with jacket. OUT

197.0	2.0	2.3	.039	60.	637.	554.	62.	62.	742.	799.	653.	782.	2063.	5510.	7573.	3.8	.189	1020.
198.0	2.0	2.3	.035	60.	639.	556.	62.	62.	743.	799.	653.	782.	1839.	5535.	7374.	3.7	.189	991.
199.0	2.0	2.3	.031	60.	641.	559.	62.	62.	743.	800.	653.	782.	1622.	5558.	7181.	3.6	.190	960.
200.0	2.0	2.2	.027	60.	643.	562.	62.	62.	744.	800.	653.	782.	1412.	5581.	6994.	3.4	.190	926.

TMID effect of FOS



Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)=      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.000000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	120.0	135.2	2.0	659.5	60.0	.024	7043.1
.0	130.0	130.7	2.0	659.5	60.0	.030	7474.3
.0	140.0	126.5	2.0	659.5	60.0	.035	7652.4
.0	150.0	123.0	2.0	659.4	60.0	.035	7510.4
.0	160.0	120.2	2.0	659.4	60.0	.032	7440.8
.0	170.0	117.3	2.0	659.4	60.0	.030	7374.2
.0	180.0	114.6	2.0	659.4	60.0	.028	7374.0



## Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction = 9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) = 15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)= 22.700000

```

```

at failure (burst pressure)/(tank pressure) = 1.200000

```

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	30.0	167.9	2.0	629.7	60.0	.024	7177.8
.0	40.0	162.6	2.0	629.6	60.0	.030	7422.4
.0	50.0	157.1	2.0	629.7	60.0	.038	7673.2
.0	60.0	151.6	2.0	629.6	60.0	.047	8236.9
.0	70.0	145.8	2.0	629.6	60.0	.058	8834.0
.0	80.0	140.3	2.0	629.6	60.0	.071	9303.8
.0	90.0	134.6	2.0	629.6	60.0	.086	10153.7
.0	100.0	128.9	2.0	629.6	60.0	.104	11089.4
.0	110.0	123.3	2.0	629.6	60.0	.122	11782.8
.0	120.0	118.2	2.0	629.7	60.0	.138	12488.7
.0	130.0	114.8	2.0	629.6	60.0	.140	12828.6
.0	140.0	112.1	2.0	629.7	60.0	.137	12431.7
.0	150.0	109.5	2.0	629.6	60.0	.134	12448.7
.0	160.0	107.2	2.0	629.6	60.0	.131	12177.0
.0	170.0	104.9	2.0	629.6	60.0	.128	12320.0
.0	180.0	102.7	2.0	629.6	60.0	.125	12101.5

## Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K) =      22.700000

```

```

at failure (burst pressure)/(tank pressure) =      1.300000

```

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	168.8	2.0	614.7	60.0	.054	8606.4
.0	20.0	163.4	2.0	614.7	60.0	.062	8903.4
.0	30.0	158.1	2.0	614.7	60.0	.072	9291.9
.0	40.0	152.5	2.0	614.8	60.0	.083	9950.0
.0	50.0	146.6	2.0	614.7	60.0	.097	10644.5
.0	60.0	140.6	2.0	614.8	60.0	.113	11443.3
.0	70.0	134.3	2.0	614.7	60.0	.132	12263.7
.0	80.0	128.2	2.0	614.7	60.0	.155	13274.8
.0	90.0	121.9	2.0	614.7	60.0	.181	14769.3
.0	100.0	115.6	2.0	614.7	60.0	.208	15977.6
.0	110.0	110.2	2.0	614.7	60.0	.230	16873.8
.0	120.0	107.1	2.0	614.8	60.0	.232	16903.9
.0	130.0	104.7	2.0	614.8	60.0	.228	17002.6
.0	140.0	102.5	2.0	614.8	60.0	.224	16717.6
.0	150.0	100.2	2.0	614.7	60.0	.221	16434.7
.0	160.0	98.2	2.0	614.7	60.0	.217	16277.7
.0	170.0	96.2	2.0	614.7	60.0	.213	16091.4
.0	180.0	94.4	2.0	614.7	60.0	.209	15979.9

Tank Model with Insulation Defects (TMID v1.0)

input data

propane

fire temp (deg C) = 816.000000  
 fire emmissivity = 1.000000  
 fire conv h (W/m^2K) = 0.000000E+00  
 fire exposure frac = 1.000000  
 tank D (m) = 3.020000  
 tank L/D = 5.770000  
 tank volume (m^3) = 124.820600  
 tank initial fill fraction = 9.000000E-01  
 wall thick (mm) = 17.500000  
 PRV operating P (MPa) = 2.000000  
 surface emmissivity = 9.000000E-01  
 lading initial temp(deg C) = 15.600000  
 jacket gap (mm) = 13.000000  
 insul defect length (m) = 17.425400  
 constant insulation conductance (W/m^2 K)= 22.700000

at failure (burst pressure)/(tank pressure) = 1.400000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	154.0	2.0	599.8	60.0	.136	12595.8
.0	20.0	148.5	2.0	599.8	60.0	.149	13097.8
.0	30.0	143.1	2.0	599.9	60.0	.165	13710.5
.0	40.0	137.2	2.0	599.9	60.0	.184	14646.3
.0	50.0	130.9	2.0	599.8	60.0	.206	15974.4
.0	60.0	124.4	2.0	599.8	60.0	.233	17073.6
.0	70.0	117.5	2.0	599.8	60.0	.263	18585.4
.0	80.0	110.8	2.0	599.8	60.0	.298	20346.4
.0	90.0	104.2	2.0	599.8	60.0	.333	21802.0
.0	100.0	99.0	2.0	599.8	60.0	.357	22854.7
.0	110.0	96.8	2.0	599.9	60.0	.354	23052.4
.0	120.0	94.8	2.0	599.9	60.0	.349	22815.8
.0	130.0	92.9	2.0	599.8	60.0	.344	22647.5
.0	140.0	91.1	2.0	599.8	60.0	.340	22021.5
.0	150.0	89.2	2.0	599.8	60.0	.335	21890.3
.0	160.0	87.7	2.0	599.8	60.0	.330	21898.4
.0	170.0	86.1	2.0	599.8	60.0	.325	21323.8
.0	180.0	84.5	2.0	599.8	60.0	.320	21365.7

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)=      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.500000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	131.3	2.0	584.9	60.0	.289	19721.5
.0	20.0	126.1	2.0	584.9	60.0	.308	20539.9
.0	30.0	120.8	2.0	585.0	60.0	.331	21869.8
.0	40.0	114.8	2.0	585.0	60.0	.358	23211.5
.0	50.0	108.5	2.0	584.9	60.0	.390	24583.0
.0	60.0	102.0	2.0	585.0	60.0	.425	26075.6
.0	70.0	95.4	2.0	584.9	60.0	.462	28025.5
.0	80.0	89.8	2.0	584.9	60.0	.495	29754.3
.0	90.0	86.5	2.0	584.9	60.0	.505	30097.0
.0	100.0	84.8	2.0	584.9	60.0	.499	29950.0
.0	110.0	83.4	2.0	585.0	60.0	.491	29386.5
.0	120.0	81.9	2.0	585.0	60.0	.485	29339.8
.0	130.0	80.5	2.0	584.9	60.0	.478	28831.6
.0	140.0	79.2	2.0	585.0	60.0	.471	28348.5
.0	150.0	77.8	2.0	584.9	60.0	.465	28399.8
.0	160.0	76.6	2.0	584.9	60.0	.459	28023.8
.0	170.0	75.4	2.0	584.9	60.0	.452	27582.2
.0	180.0	74.3	2.0	584.9	60.0	.445	27199.9

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)=      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.600000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	101.3	2.0	570.0	60.0	.529	31083.7
.0	20.0	97.5	2.0	570.0	60.0	.545	31935.4
.0	30.0	93.6	2.0	570.1	60.0	.564	32902.2
.0	40.0	89.4	2.0	570.1	60.0	.584	33811.7
.0	50.0	85.3	2.0	570.0	60.0	.604	34684.1
.0	60.0	81.6	2.0	570.1	60.0	.620	35615.1
.0	70.0	78.3	2.0	570.0	60.0	.631	35990.2
.0	80.0	76.5	2.0	570.0	60.0	.629	35994.2
.0	90.0	75.2	2.0	570.0	60.0	.621	35502.6
.0	100.0	74.0	2.0	570.0	60.0	.613	35518.1
.0	110.0	72.9	2.0	570.1	60.0	.605	35097.0
.0	120.0	71.8	2.0	570.1	60.0	.597	34672.8
.0	130.0	70.8	2.0	570.0	60.0	.589	34296.3
.0	140.0	69.8	2.0	570.1	60.0	.581	33945.4
.0	150.0	68.8	2.0	570.0	60.0	.574	33567.2
.0	160.0	67.9	2.0	570.0	60.0	.566	33314.4
.0	170.0	67.0	2.0	570.0	60.0	.558	32992.9
.0	180.0	66.1	2.0	570.0	60.0	.551	32108.3

## Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction = 9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) = 15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K) = 22.700000

```

```

at failure (burst pressure)/(tank pressure) = 1.700000

```

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	.0	92.6	2.0	555.1	60.0	.617	35438.7
.0	10.0	82.2	2.0	555.1	60.0	.695	38928.0
.0	20.0	80.5	2.0	555.1	60.0	.697	39164.9
.0	30.0	78.8	2.0	555.2	60.0	.700	39470.1
.0	40.0	76.9	2.0	555.2	60.0	.703	39663.4
.0	50.0	74.8	2.0	555.2	60.0	.705	39765.5
.0	60.0	73.0	2.0	555.2	60.0	.706	39872.7
.0	70.0	71.2	2.0	555.1	60.0	.703	39364.5
.0	80.0	70.1	2.0	555.1	60.0	.696	38952.0
.0	90.0	69.0	2.0	555.1	60.0	.688	39051.5
.0	100.0	67.9	2.0	555.1	60.0	.680	38645.0
.0	110.0	66.9	2.0	555.2	60.0	.672	38305.6
.0	120.0	65.9	2.0	555.2	60.0	.665	37963.3
.0	130.0	65.0	2.0	555.2	60.0	.657	37103.8
.0	140.0	64.2	2.0	555.1	60.0	.649	36822.0
.0	150.0	63.2	2.0	555.1	60.0	.642	36512.6
.0	160.0	62.5	2.0	555.1	60.0	.634	36330.2
.0	170.0	61.7	2.0	555.1	60.0	.627	36078.1



tank model with jacket.OUT

.0	180.0	60.9	2.0	555.0	60.0	.619	35889.4
----	-------	------	-----	-------	------	------	---------

TMID effect of fire T

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D               =      5.770000
tank volume (m^3)      =      122.357100
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      0.000000E+00
angle to defect bot (deg) =      90.000000
constant insulation conductance (W/m^2 K)=      22.700000
    
```

time (min)	press (MPa)	pbst (MPa)	fill (MPa)	tlad (C)	tlad (C)	tlad (C)	twvd (C)	twvi (C)	twli (C)	twld (C)	tjvd (C)	tjvi (C)	tjld (C)	tjli (C)	mliq (kg)	mvap (kg)	mtot (kg)	mdot (kg/s)	kins (W/mK)	qdottot (kW)
1.0	.7	6.4	.900	16.	19.	20.	17.	17.	17.	394.	389.	394.	389.	389.	55703.	197.	55900.	.0	.295	878.
2.0	.7	6.4	.902	17.	37.	31.	21.	19.	19.	591.	619.	591.	591.	618.	55700.	197.	55897.	.0	.295	1832.
3.0	.7	6.4	.904	18.	67.	46.	24.	20.	20.	642.	712.	641.	641.	710.	55695.	197.	55892.	.0	.295	2284.
4.0	.7	6.4	.906	18.	99.	61.	25.	22.	22.	652.	741.	651.	651.	738.	55697.	197.	55894.	.0	.295	2426.
5.0	.7	6.4	.909	19.	131.	75.	26.	23.	23.	655.	749.	652.	652.	745.	55689.	196.	55886.	.0	.295	2468.
6.0	.8	6.4	.912	20.	163.	90.	27.	24.	24.	656.	752.	653.	653.	747.	55685.	195.	55880.	.0	.295	2496.

7.0	.8	6.3	.914	21.	194.	104.	28.	25.	658.	754.	653.	747.	55676.	195.	55870.	.0	.295	2516.
8.0	.8	6.3	.917	22.	225.	118.	29.	25.	660.	755.	653.	748.	55665.	194.	55858.	.0	.295	2541.
9.0	.8	6.2	.920	23.	254.	132.	30.	26.	662.	757.	653.	748.	55662.	192.	55853.	.0	.295	2560.
10.0	.8	6.1	.922	24.	282.	145.	31.	27.	665.	758.	653.	748.	55654.	190.	55844.	.0	.295	2592.
11.0	.9	6.0	.925	25.	309.	158.	32.	29.	667.	759.	653.	748.	55648.	188.	55836.	.0	.295	2618.
12.0	.9	5.9	.929	27.	334.	171.	33.	30.	670.	760.	653.	748.	55656.	184.	55840.	.0	.295	2642.
13.0	.9	5.7	.932	28.	358.	183.	34.	31.	674.	761.	653.	748.	55670.	179.	55849.	.0	.295	2676.
14.0	.9	5.5	.936	29.	380.	195.	35.	32.	677.	763.	653.	748.	55677.	175.	55852.	.0	.295	2710.
15.0	1.0	5.3	.939	30.	400.	206.	36.	33.	680.	764.	653.	748.	55680.	170.	55850.	.0	.295	2744.
16.0	1.0	5.1	.943	31.	419.	217.	37.	34.	684.	765.	653.	748.	55679.	165.	55844.	.0	.295	2774.
critical wall temperature reached																		
17.0	1.0	5.0	.946	32.	436.	228.	39.	35.	687.	766.	653.	748.	55670.	160.	55830.	.0	.295	2810.
18.0	1.1	4.8	.949	33.	451.	238.	40.	36.	690.	767.	653.	749.	55667.	154.	55821.	.0	.295	2838.
19.0	1.1	4.6	.953	34.	465.	248.	41.	37.	693.	768.	653.	749.	55662.	147.	55809.	.0	.295	2871.
20.0	1.1	4.5	.957	35.	477.	258.	42.	38.	696.	768.	653.	749.	55657.	139.	55795.	.0	.295	2899.
21.0	1.2	4.3	.961	36.	488.	267.	43.	39.	698.	769.	653.	749.	55652.	130.	55782.	.0	.295	2931.
22.0	1.2	4.2	.965	38.	498.	276.	44.	40.	701.	770.	653.	749.	55653.	120.	55773.	.0	.295	2957.
23.0	1.2	4.1	.969	39.	507.	284.	45.	42.	703.	771.	653.	749.	55678.	107.	55785.	.0	.295	2986.
24.0	1.3	4.0	.974	40.	514.	292.	46.	43.	705.	772.	653.	749.	55705.	93.	55798.	.0	.295	3019.
25.0	1.3	3.9	.979	41.	520.	299.	48.	44.	707.	772.	653.	749.	55726.	78.	55804.	.0	.295	3052.
26.0	1.3	3.8	.984	42.	526.	306.	49.	45.	708.	773.	653.	749.	55745.	61.	55806.	.0	.295	3085.
27.0	1.4	3.8	.989	43.	531.	313.	50.	46.	709.	774.	653.	750.	55755.	44.	55799.	.0	.295	3125.
28.0	1.4	3.7	.993	45.	535.	319.	51.	48.	711.	774.	653.	750.	55756.	27.	55783.	.0	.295	3173.
29.0	1.5	5.1	.998	46.	396.	244.	53.	49.	710.	774.	653.	750.	55760.	7.	55767.	.0	.295	3342.
30.0	1.5	6.41.000	47.	56.	51.	51.	54.	50.	663.	757.	653.	750.	55568.	0.	55568.	4.7	.295	3338.
31.0	1.5	6.41.000	48.	55.	51.	51.	55.	51.	655.	752.	653.	750.	55281.	0.	55281.	5.2	.295	3334.
32.0	1.6	6.41.000	50.	56.	53.	53.	56.	53.	654.	751.	653.	750.	54971.	0.	54971.	5.2	.295	3332.
33.0	1.6	6.41.000	51.	57.	54.	54.	58.	54.	653.	750.	653.	750.	54663.	0.	54663.	5.1	.295	3328.
34.0	1.7	6.41.000	52.	59.	55.	55.	59.	55.	653.	750.	653.	750.	54358.	0.	54358.	5.3	.295	3324.
35.0	1.7	6.41.000	53.	60.	56.	56.	60.	56.	653.	750.	653.	750.	54042.	0.	54042.	5.2	.295	3321.
36.0	1.8	6.41.000	55.	61.	58.	58.	61.	58.	653.	751.	653.	751.	53729.	0.	53729.	5.2	.295	3316.
37.0	1.8	6.41.000	56.	62.	59.	59.	63.	59.	653.	751.	653.	751.	53416.	0.	53416.	5.6	.295	3312.
38.0	1.9	6.41.000	57.	64.	60.	60.	64.	60.	653.	751.	653.	751.	53079.	0.	53079.	5.6	.295	3308.
39.0	1.9	6.41.000	58.	65.	61.	61.	65.	61.	653.	751.	653.	751.	52745.	0.	52745.	5.6	.295	3303.
40.0	2.0	6.41.000	60.	66.	63.	63.	66.	63.	654.	751.	654.	751.	52412.	0.	52412.	5.9	.295	3299.
41.0	2.0	6.4	.990	60.	87.	72.	67.	63.	654.	751.	654.	751.	51793.	58.	51851.	11.4	.295	3070.
42.0	2.0	6.4	.977	60.	120.	87.	67.	63.	655.	753.	654.	751.	51129.	131.	51260.	10.8	.295	2920.
43.0	2.0	6.4	.965	60.	153.	102.	67.	63.	656.	754.	654.	751.	50491.	201.	50692.	10.4	.295	2813.
44.0	2.0	6.4	.953	60.	184.	116.	67.	63.	657.	755.	654.	751.	49872.	269.	50141.	10.2	.295	2750.

45.0	2.0	6.3	.941	60.	215.	130.	67.	63.	659.	756.	654.	751.	49267.	335.	49602.	10.0	.295	2698.
46.0	2.0	6.2	.930	60.	245.	143.	67.	63.	661.	758.	654.	751.	48672.	400.	49072.	9.8	.295	2654.
47.0	2.0	6.2	.919	60.	273.	156.	67.	63.	664.	759.	654.	751.	48086.	465.	48550.	9.7	.295	2618.
48.0	2.0	6.0	.908	60.	301.	169.	67.	63.	667.	760.	654.	751.	47506.	528.	48034.	9.6	.295	2594.
49.0	2.0	5.9	.897	60.	327.	181.	67.	63.	670.	761.	654.	751.	46931.	591.	47523.	9.5	.295	2573.
50.0	2.0	5.7	.886	60.	351.	193.	67.	63.	673.	762.	654.	751.	46361.	654.	47014.	9.5	.295	2558.
51.0	2.0	5.6	.875	60.	374.	205.	67.	63.	676.	764.	654.	751.	45792.	716.	46508.	9.5	.295	2550.
52.0	2.0	5.4	.864	60.	395.	216.	67.	63.	679.	765.	654.	751.	45226.	778.	46004.	9.4	.295	2544.
53.0	2.0	5.2	.853	60.	414.	228.	67.	63.	683.	766.	654.	751.	44661.	840.	45501.	9.4	.295	2540.
54.0	2.0	5.1	.843	60.	432.	239.	67.	63.	686.	767.	654.	751.	44096.	902.	44998.	9.4	.295	2540.
55.0	2.0	4.9	.832	60.	449.	249.	67.	63.	689.	768.	654.	751.	43531.	964.	44495.	9.4	.295	2542.
56.0	2.0	4.7	.821	60.	463.	260.	67.	63.	692.	769.	654.	751.	42965.	1026.	43991.	9.4	.295	2543.
57.0	2.0	4.5	.810	60.	477.	270.	67.	63.	695.	769.	654.	751.	42400.	1088.	43488.	9.4	.295	2544.
58.0	2.0	4.3	.799	60.	488.	280.	67.	63.	698.	770.	654.	751.	41834.	1150.	42984.	9.4	.295	2548.
59.0	2.0	4.2	.788	60.	499.	289.	67.	63.	701.	771.	654.	751.	41267.	1212.	42479.	9.4	.295	2549.
60.0	2.0	4.1	.778	60.	508.	299.	67.	63.	703.	772.	654.	751.	40700.	1274.	41974.	9.5	.295	2551.
61.0	2.0	3.9	.767	60.	517.	308.	67.	63.	705.	773.	654.	751.	40132.	1337.	41469.	9.5	.295	2553.
62.0	2.0	3.8	.756	60.	524.	317.	67.	63.	707.	774.	654.	751.	39564.	1399.	40963.	9.5	.295	2553.
63.0	2.0	3.8	.745	60.	531.	325.	67.	63.	709.	774.	654.	751.	38996.	1461.	40457.	9.5	.295	2553.
64.0	2.0	3.7	.734	60.	536.	333.	67.	63.	711.	775.	654.	751.	38428.	1523.	39952.	9.5	.295	2551.
65.0	2.0	3.6	.723	60.	542.	341.	67.	63.	712.	776.	654.	751.	37861.	1586.	39447.	9.5	.295	2551.
66.0	2.0	3.5	.713	60.	546.	349.	67.	63.	714.	777.	654.	751.	37294.	1648.	38942.	9.4	.295	2547.
67.0	2.0	3.5	.702	60.	550.	356.	67.	63.	715.	777.	654.	751.	36728.	1710.	38438.	9.4	.295	2545.
68.0	2.0	3.4	.691	60.	554.	363.	67.	63.	716.	778.	654.	751.	36162.	1772.	37934.	9.4	.295	2539.
69.0	2.0	3.4	.680	60.	557.	370.	67.	63.	717.	779.	654.	751.	35598.	1834.	37431.	9.4	.295	2536.
70.0	2.0	3.4	.669	60.	560.	377.	67.	63.	718.	779.	654.	751.	35034.	1896.	36930.	9.4	.295	2530.
71.0	2.0	3.3	.659	60.	562.	383.	67.	63.	718.	780.	654.	751.	34472.	1957.	36430.	9.4	.295	2524.
72.0	2.0	3.3	.648	60.	565.	389.	67.	63.	719.	780.	654.	751.	33912.	2019.	35930.	9.3	.295	2516.
73.0	2.0	3.3	.637	60.	567.	395.	67.	63.	720.	781.	654.	751.	33353.	2080.	35433.	9.3	.295	2509.
74.0	2.0	3.2	.627	60.	569.	400.	67.	63.	720.	781.	654.	751.	32795.	2141.	34936.	9.3	.295	2501.
75.0	2.0	3.2	.616	60.	571.	405.	67.	63.	721.	782.	654.	751.	32240.	2202.	34442.	9.2	.295	2493.
AFFTAC model with fos = 1.600000																		
75.6	2.0	3.2	.610	60.	572.	408.	67.	63.	721.	782.	654.	751.	31916.	2237.	34442.	9.2	.295	2487.
76.0	2.0	3.2	.605	60.	572.	410.	67.	63.	721.	782.	654.	751.	31686.	2263.	33949.	9.2	.295	2484.
77.0	2.0	3.2	.595	60.	574.	415.	67.	63.	722.	783.	654.	751.	31134.	2323.	33457.	9.2	.295	2476.
78.0	2.0	3.2	.584	60.	575.	420.	67.	63.	722.	783.	654.	751.	30585.	2383.	32968.	9.1	.295	2466.
79.0	2.0	3.1	.574	60.	577.	424.	67.	63.	723.	783.	654.	751.	30037.	2443.	32481.	9.1	.295	2457.
80.0	2.0	3.1	.563	60.	578.	429.	67.	63.	723.	784.	654.	751.	29492.	2503.	31995.	9.1	.295	2445.
81.0	2.0	3.1	.553	60.	579.	433.	67.	63.	723.	784.	654.	751.	28949.	2563.	31512.	9.0	.295	2435.



82.0	2.0	3.1	.543	60.	581.	436.	67.	63.	724.	784.	654.	751.	28409.	2622.	31031.	9.0	.295	2424.
83.0	2.0	3.1	.532	60.	582.	440.	67.	63.	724.	785.	654.	751.	27871.	2681.	30552.	8.9	.295	2412.
84.0	2.0	3.0	.522	60.	583.	444.	67.	63.	725.	785.	654.	751.	27335.	2740.	30075.	8.9	.295	2401.
85.0	2.0	3.0	.512	60.	584.	447.	67.	63.	725.	785.	654.	751.	26803.	2798.	29601.	8.9	.295	2389.
86.0	2.0	3.0	.502	60.	585.	451.	67.	63.	725.	786.	654.	751.	26273.	2856.	29129.	8.8	.295	2375.
87.0	2.0	3.0	.492	60.	586.	454.	63.	63.	726.	786.	653.	751.	25745.	2914.	28659.	8.8	.295	2368.
88.0	2.0	3.0	.482	60.	587.	457.	63.	63.	726.	786.	653.	751.	25220.	2972.	28191.	8.7	.295	2358.
89.0	2.0	3.0	.472	60.	588.	460.	63.	63.	726.	787.	653.	751.	24696.	3029.	27725.	8.7	.295	2351.
90.0	2.0	3.0	.462	60.	589.	462.	63.	63.	726.	787.	653.	751.	24174.	3086.	27260.	8.7	.295	2341.
91.0	2.0	3.0	.452	60.	590.	465.	63.	63.	727.	787.	653.	751.	23654.	3143.	26798.	8.6	.295	2332.
92.0	2.0	2.9	.442	60.	591.	468.	63.	63.	727.	787.	653.	751.	23137.	3200.	26337.	8.6	.295	2321.
93.0	2.0	2.9	.432	60.	592.	470.	63.	63.	727.	787.	653.	751.	22622.	3256.	25878.	8.6	.295	2312.
94.0	2.0	2.9	.422	60.	592.	472.	63.	63.	728.	788.	653.	751.	22109.	3313.	25421.	8.5	.295	2300.
95.0	2.0	2.9	.413	60.	593.	475.	63.	63.	728.	788.	653.	751.	21598.	3369.	24967.	8.5	.295	2290.
96.0	2.0	2.9	.403	60.	594.	477.	63.	63.	728.	788.	653.	751.	21090.	3424.	24514.	8.4	.295	2279.
97.0	2.0	2.9	.393	60.	595.	479.	63.	63.	728.	788.	653.	751.	20584.	3480.	24064.	8.4	.295	2267.
98.0	2.0	2.9	.384	60.	596.	481.	63.	63.	728.	788.	653.	751.	20081.	3535.	23616.	8.4	.295	2256.
99.0	2.0	2.9	.374	60.	596.	483.	63.	63.	729.	789.	653.	751.	19581.	3590.	23171.	8.3	.295	2243.
100.0	2.0	2.9	.365	60.	597.	485.	63.	63.	729.	789.	653.	751.	19083.	3644.	22728.	8.3	.295	2231.
101.0	2.0	2.8	.355	60.	598.	487.	63.	63.	729.	789.	653.	751.	18589.	3699.	22287.	8.2	.295	2218.
102.0	2.0	2.8	.346	60.	599.	489.	63.	63.	729.	789.	653.	751.	18097.	3753.	21849.	8.2	.295	2205.
103.0	2.0	2.8	.336	60.	599.	491.	63.	63.	730.	789.	653.	751.	17608.	3806.	21414.	8.1	.295	2192.
104.0	2.0	2.8	.327	60.	600.	493.	63.	63.	730.	789.	653.	751.	17122.	3859.	20981.	8.1	.295	2178.
105.0	2.0	2.8	.318	60.	601.	495.	63.	63.	730.	790.	653.	751.	16639.	3912.	20551.	8.0	.295	2164.
106.0	2.0	2.8	.309	60.	602.	496.	63.	63.	730.	790.	653.	751.	16159.	3965.	20124.	8.0	.295	2150.
107.0	2.0	2.8	.300	60.	603.	498.	63.	63.	731.	790.	653.	751.	15683.	4017.	19700.	7.9	.295	2135.
108.0	2.0	2.8	.291	60.	603.	500.	63.	63.	731.	790.	653.	751.	15209.	4069.	19279.	7.9	.295	2120.
109.0	2.0	2.8	.282	60.	604.	502.	63.	63.	731.	790.	653.	751.	14740.	4121.	18860.	7.8	.295	2104.
110.0	2.0	2.7	.273	60.	605.	503.	63.	63.	731.	790.	653.	751.	14273.	4172.	18445.	7.7	.295	2089.
111.0	2.0	2.7	.264	60.	606.	505.	63.	63.	731.	790.	653.	751.	13810.	4223.	18033.	7.7	.295	2073.
112.0	2.0	2.7	.255	60.	607.	507.	63.	63.	732.	790.	653.	751.	13351.	4273.	17624.	7.6	.295	2057.
113.0	2.0	2.7	.246	60.	607.	509.	63.	63.	732.	791.	653.	751.	12895.	4323.	17218.	7.6	.295	2040.
114.0	2.0	2.7	.238	60.	608.	510.	63.	63.	733.	791.	653.	751.	12443.	4372.	16815.	7.5	.295	2024.
115.0	2.0	2.7	.229	60.	609.	512.	63.	63.	733.	791.	653.	751.	11995.	4422.	16416.	7.4	.295	2006.
116.0	2.0	2.7	.221	60.	610.	514.	63.	63.	733.	791.	653.	751.	11550.	4470.	16021.	7.4	.295	1988.
117.0	2.0	2.7	.212	60.	611.	516.	63.	63.	733.	791.	653.	751.	11110.	4519.	15629.	7.3	.295	1970.
118.0	2.0	2.7	.204	60.	612.	518.	63.	63.	734.	791.	653.	751.	10674.	4566.	15240.	7.2	.295	1952.
119.0	2.0	2.6	.196	60.	613.	519.	63.	63.	734.	792.	653.	751.	10242.	4614.	14855.	7.2	.295	1933.
120.0	2.0	2.6	.187	60.	614.	521.	63.	63.	734.	792.	653.	751.	9814.	4661.	14474.	7.1	.295	1914.



121.0	2.0	2.6	.179	60.	615.	523.	63.	63.	735.	792.	653.	751.	9390.	4707.	14097.	7.0	.295	1894.
122.0	2.0	2.6	.171	60.	616.	525.	63.	63.	735.	792.	653.	751.	8972.	4753.	13725.	6.9	.295	1873.
123.0	2.0	2.6	.163	60.	617.	527.	63.	63.	735.	792.	653.	751.	8557.	4798.	13356.	6.9	.295	1851.
124.0	2.0	2.6	.156	60.	618.	529.	63.	63.	736.	792.	653.	751.	8148.	4843.	12991.	6.8	.295	1830.
125.0	2.0	2.6	.148	60.	619.	531.	63.	63.	736.	793.	653.	751.	7743.	4888.	12631.	6.7	.295	1807.
126.0	2.0	2.5	.140	60.	620.	533.	63.	63.	736.	793.	653.	751.	7344.	4931.	12275.	6.6	.295	1785.
127.0	2.0	2.5	.133	60.	621.	535.	63.	63.	737.	793.	653.	751.	6949.	4975.	11924.	6.5	.295	1761.
128.0	2.0	2.5	.125	60.	622.	537.	63.	63.	737.	793.	653.	751.	6560.	5017.	11578.	6.4	.295	1736.
129.0	2.0	2.5	.118	60.	624.	539.	63.	63.	737.	793.	653.	751.	6177.	5059.	11237.	6.3	.295	1710.
130.0	2.0	2.5	.111	60.	625.	541.	63.	63.	738.	793.	653.	751.	5800.	5101.	10900.	6.2	.295	1683.
131.0	2.0	2.5	.104	60.	626.	543.	63.	63.	738.	794.	653.	751.	5428.	5141.	10570.	6.1	.295	1656.
132.0	2.0	2.4	.097	60.	627.	546.	63.	63.	739.	794.	653.	751.	5063.	5182.	10244.	6.0	.295	1628.
133.0	2.0	2.4	.090	60.	629.	548.	63.	63.	739.	794.	653.	751.	4704.	5221.	9925.	5.9	.295	1598.
134.0	2.0	2.4	.083	60.	630.	550.	63.	63.	740.	794.	653.	751.	4352.	5259.	9611.	5.8	.295	1567.
135.0	2.0	2.4	.076	60.	632.	553.	63.	63.	740.	794.	653.	751.	4007.	5297.	9304.	5.7	.295	1534.
136.0	2.0	2.4	.070	60.	633.	555.	63.	63.	741.	795.	653.	751.	3669.	5334.	9004.	5.6	.295	1499.
137.0	2.0	2.3	.064	60.	635.	558.	63.	63.	741.	795.	653.	751.	3340.	5370.	8710.	5.4	.295	1463.
138.0	2.0	2.3	.058	60.	636.	561.	63.	63.	742.	795.	653.	751.	3018.	5406.	8424.	5.3	.295	1425.
139.0	2.0	2.3	.052	60.	638.	563.	63.	63.	742.	795.	653.	751.	2706.	5440.	8146.	5.1	.295	1385.
140.0	2.0	2.3	.046	60.	640.	566.	63.	63.	743.	796.	653.	751.	2402.	5473.	7876.	5.0	.295	1341.
141.0	2.0	2.3	.040	60.	642.	569.	63.	63.	744.	796.	653.	751.	2109.	5505.	7614.	4.8	.295	1295.
142.0	2.0	2.2	.035	60.	644.	572.	63.	63.	744.	796.	653.	751.	1826.	5536.	7363.	4.6	.295	1246.
143.0	2.0	2.2	.030	60.	646.	575.	63.	63.	745.	796.	653.	751.	1555.	5566.	7121.	4.4	.295	1191.
144.0	2.0	2.2	.025	60.	648.	579.	63.	63.	746.	797.	653.	751.	1296.	5594.	6891.	4.2	.295	1132.
145.0	2.0	2.1	.020	60.	651.	582.	63.	63.	747.	797.	653.	751.	1051.	5621.	6673.	4.0	.295	1067.
145.0	2.0	2.1	.020	60.	651.	582.	63.	63.	747.	797.	653.	751.	1048.	5622.	6673.	4.0	.295	1066.

# Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      871.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D               =      5.770000
tank volume (m^3)      =      122.357100
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      0.000000E+00
angle to defect bot (deg) =      90.000000
constant insulation conductance (W/m^2 K)=      22.700000
    
```

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twvd C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	miq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.900	16.	21.	21.	18.	18.	467.	465.	467.	465.	55703.	197.	55900.	.0	.295	1099.
2.0	.7	6.4	.902	17.	47.	34.	23.	20.	659.	711.	659.	710.	55699.	197.	55896.	.0	.295	2230.
3.0	.7	6.4	.905	18.	84.	50.	26.	21.	695.	788.	694.	786.	55697.	197.	55894.	.0	.295	2642.
4.0	.7	6.4	.908	19.	124.	67.	27.	22.	701.	806.	699.	803.	55696.	196.	55892.	.0	.295	2750.
5.0	.7	6.4	.911	20.	163.	83.	28.	23.	703.	811.	699.	807.	55689.	196.	55885.	.0	.295	2784.
6.0	.8	6.3	.914	21.	202.	99.	29.	24.	704.	813.	699.	808.	55681.	195.	55876.	.0	.295	2814.

tank model with jacket.OUT

7.0	.8	6.3	.917	22.	239.	114.	30.	26.	707.	814.	699.	808.	55673.	194.	55866.	.0	.295	2843.
8.0	.8	6.2	.920	23.	275.	129.	32.	27.	709.	815.	699.	808.	55669.	191.	55861.	.0	.295	2871.
9.0	.8	6.0	.923	25.	309.	144.	33.	28.	712.	817.	699.	808.	55662.	189.	55851.	.0	.295	2909.
10.0	.9	5.8	.926	26.	341.	158.	34.	29.	716.	818.	700.	808.	55665.	187.	55851.	.0	.295	2945.
11.0	.9	5.6	.930	27.	371.	172.	35.	30.	719.	819.	700.	808.	55679.	182.	55860.	.0	.295	2987.
12.0	.9	5.3	.934	28.	399.	186.	36.	31.	723.	820.	700.	808.	55683.	177.	55860.	.0	.295	3027.
13.0	1.0	5.0	.938	29.	425.	199.	37.	33.	727.	821.	700.	808.	55678.	172.	55851.	.0	.295	3076.
critical wall temperature reached																		
14.0	1.0	4.9	.941	30.	448.	212.	39.	34.	731.	822.	700.	808.	55672.	167.	55839.	.0	.295	3118.
15.0	1.0	4.6	.945	32.	469.	224.	40.	35.	735.	823.	700.	809.	55668.	161.	55829.	.0	.295	3163.
16.0	1.1	4.3	.949	33.	488.	236.	41.	36.	739.	824.	700.	809.	55663.	155.	55818.	.0	.295	3204.
17.0	1.1	4.1	.953	34.	505.	248.	42.	37.	742.	825.	700.	809.	55658.	146.	55804.	.0	.295	3246.
18.0	1.1	3.9	.958	36.	519.	259.	44.	39.	746.	826.	700.	809.	55684.	135.	55819.	.0	.295	3278.
19.0	1.2	3.7	.963	37.	532.	269.	45.	40.	749.	827.	700.	809.	55703.	123.	55826.	.0	.295	3328.
20.0	1.2	3.6	.968	38.	543.	280.	46.	41.	751.	827.	700.	809.	55720.	109.	55830.	.0	.295	3364.
21.0	1.3	3.5	.973	39.	552.	289.	48.	43.	754.	828.	700.	809.	55729.	96.	55825.	.0	.295	3410.
22.0	1.3	3.4	.978	41.	560.	298.	49.	44.	756.	829.	700.	809.	55729.	81.	55811.	.0	.295	3451.
23.0	1.3	3.3	.983	42.	567.	307.	50.	45.	758.	830.	700.	809.	55728.	65.	55793.	.0	.295	3488.
24.0	1.4	3.2	.988	43.	572.	315.	52.	47.	759.	830.	700.	809.	55730.	46.	55777.	.0	.295	3548.
25.0	1.4	3.1	.994	45.	577.	323.	53.	48.	761.	831.	700.	810.	55749.	25.	55774.	.0	.295	3605.
26.0	1.5	6.41	.000	46.	134.	91.	54.	49.	734.	826.	700.	810.	55767.	0.	55767.	5.5	.295	3797.
27.0	1.5	6.41	.000	48.	56.	51.	56.	51.	704.	813.	700.	810.	55441.	0.	55441.	5.4	.295	3792.
28.0	1.6	6.41	.000	49.	57.	52.	57.	52.	700.	811.	700.	810.	55100.	0.	55100.	5.9	.295	3793.
29.0	1.6	6.41	.000	51.	59.	54.	59.	54.	700.	810.	700.	810.	54747.	0.	54747.	5.9	.295	3784.
30.0	1.7	6.41	.000	52.	60.	55.	60.	55.	700.	810.	700.	810.	54395.	0.	54395.	5.8	.295	3780.
31.0	1.7	6.41	.000	53.	61.	57.	62.	57.	700.	810.	700.	810.	54032.	0.	54032.	6.0	.295	3775.
32.0	1.8	6.41	.000	55.	63.	58.	63.	58.	700.	810.	700.	810.	53671.	0.	53671.	6.0	.295	3771.
33.0	1.8	6.41	.000	56.	64.	59.	64.	59.	700.	811.	700.	811.	53305.	0.	53305.	6.4	.295	3767.
34.0	1.9	6.41	.000	58.	66.	61.	66.	61.	700.	811.	700.	811.	52920.	0.	52920.	6.4	.295	3762.
35.0	2.0	6.41	.000	59.	67.	62.	67.	62.	700.	811.	700.	811.	52541.	0.	52541.	6.3	.295	3758.
36.0	2.0	6.4	.993	60.	81.	69.	68.	63.	700.	811.	700.	811.	51969.	39.	52007.	13.1	.295	3537.
37.0	2.0	6.4	.979	60.	121.	85.	68.	63.	701.	812.	700.	811.	51209.	122.	51331.	12.2	.295	3300.
38.0	2.0	6.4	.965	60.	161.	101.	68.	63.	703.	813.	700.	811.	50487.	201.	50689.	11.8	.295	3175.
39.0	2.0	6.3	.951	60.	200.	116.	68.	63.	704.	814.	700.	811.	49790.	278.	50068.	11.5	.295	3091.
40.0	2.0	6.3	.938	60.	237.	131.	68.	63.	706.	816.	700.	811.	49111.	352.	49463.	11.2	.295	3016.
41.0	2.0	6.2	.926	60.	273.	146.	68.	63.	709.	817.	700.	811.	48445.	425.	48870.	11.0	.295	2968.
42.0	2.0	6.0	.913	60.	308.	160.	68.	63.	712.	818.	700.	811.	47789.	497.	48286.	10.9	.295	2929.
43.0	2.0	5.8	.901	60.	340.	174.	68.	63.	715.	819.	700.	811.	47141.	568.	47709.	10.8	.295	2900.
44.0	2.0	5.6	.888	60.	371.	188.	68.	63.	719.	820.	700.	811.	46498.	639.	47137.	10.7	.295	2881.

45.0	2.0	5.3	.876	60.	399.	201.	68.	63.	723.	821.	700.	811.	45860.	709.	46568.	10.6	.295	2866.
46.0	2.0	5.0	.864	60.	425.	214.	68.	63.	727.	822.	700.	811.	45223.	778.	46002.	10.6	.295	2859.
47.0	2.0	4.9	.852	60.	449.	227.	68.	63.	731.	823.	700.	811.	44588.	848.	45436.	10.6	.295	2854.
48.0	2.0	4.6	.840	60.	470.	240.	68.	63.	735.	824.	700.	811.	43953.	918.	44870.	10.6	.295	2855.
49.0	2.0	4.3	.828	60.	490.	252.	68.	63.	739.	825.	700.	811.	43317.	987.	44305.	10.6	.295	2857.
50.0	2.0	4.1	.816	60.	507.	264.	68.	63.	743.	826.	700.	811.	42681.	1057.	43739.	10.6	.295	2860.
51.0	2.0	3.9	.803	60.	522.	276.	68.	63.	746.	827.	700.	811.	42045.	1127.	43172.	10.6	.295	2865.
52.0	2.0	3.7	.791	60.	535.	288.	68.	63.	749.	828.	700.	811.	41407.	1197.	42604.	10.6	.295	2870.
53.0	2.0	3.5	.779	60.	546.	299.	68.	63.	752.	829.	700.	811.	40768.	1267.	42035.	10.7	.295	2873.
54.0	2.0	3.4	.767	60.	556.	310.	68.	63.	755.	830.	700.	811.	40129.	1337.	41466.	10.7	.295	2875.
55.0	2.0	3.3	.755	60.	565.	320.	68.	63.	757.	831.	700.	811.	39489.	1407.	40897.	10.7	.295	2875.
AFFTAC model with fos = 1.600000																		
55.9	2.0	3.2	.744	60.	572.	330.	68.	63.	759.	831.	700.	811.	38924.	1469.	40897.	10.7	.295	2874.
56.0	2.0	3.2	.742	60.	572.	331.	68.	63.	759.	831.	700.	811.	38850.	1477.	40327.	10.7	.295	2876.
57.0	2.0	3.1	.730	60.	579.	341.	68.	63.	761.	832.	700.	811.	38210.	1547.	39758.	10.7	.295	2873.
58.0	2.0	3.0	.718	60.	585.	350.	68.	63.	763.	833.	700.	811.	37572.	1618.	39189.	10.6	.295	2871.
59.0	2.0	3.0	.706	60.	590.	360.	68.	63.	764.	834.	700.	811.	36933.	1687.	38621.	10.6	.295	2867.
60.0	2.0	2.9	.694	60.	594.	369.	68.	63.	765.	834.	700.	811.	36296.	1757.	38054.	10.6	.295	2862.
61.0	2.0	2.9	.681	60.	598.	377.	68.	63.	766.	835.	700.	811.	35661.	1827.	37488.	10.6	.295	2856.
62.0	2.0	2.8	.669	60.	601.	386.	68.	63.	767.	836.	700.	811.	35026.	1897.	36923.	10.6	.295	2849.
63.0	2.0	2.8	.657	60.	604.	393.	68.	63.	768.	836.	700.	811.	34394.	1966.	36360.	10.5	.295	2840.
64.0	2.0	2.7	.645	60.	606.	401.	68.	63.	769.	837.	700.	811.	33763.	2035.	35798.	10.5	.295	2831.
65.0	2.0	2.7	.633	60.	609.	408.	68.	63.	770.	837.	700.	811.	33134.	2104.	35238.	10.5	.295	2820.
66.0	2.0	2.7	.621	60.	611.	415.	68.	63.	770.	838.	700.	811.	32508.	2173.	34680.	10.4	.295	2812.
67.0	2.0	2.6	.609	60.	613.	422.	68.	63.	771.	838.	700.	811.	31883.	2241.	34125.	10.4	.295	2800.
68.0	2.0	2.6	.597	60.	615.	428.	68.	63.	771.	839.	700.	811.	31262.	2309.	33571.	10.3	.295	2789.
69.0	2.0	2.6	.585	60.	616.	434.	68.	63.	772.	839.	700.	811.	30643.	2377.	33020.	10.3	.295	2776.
70.0	2.0	2.6	.574	60.	618.	440.	68.	63.	772.	840.	700.	811.	30026.	2445.	32471.	10.2	.295	2764.
71.0	2.0	2.6	.562	60.	619.	445.	68.	63.	773.	840.	700.	811.	29413.	2512.	31925.	10.2	.295	2751.
72.0	2.0	2.5	.550	60.	621.	451.	68.	63.	773.	841.	700.	811.	28803.	2579.	31382.	10.1	.295	2737.
73.0	2.0	2.5	.539	60.	622.	456.	68.	63.	774.	841.	700.	811.	28195.	2646.	30841.	10.1	.295	2724.
74.0	2.0	2.5	.527	60.	624.	460.	68.	63.	774.	841.	700.	811.	27591.	2712.	30303.	10.0	.295	2708.
75.0	2.0	2.5	.516	60.	625.	465.	68.	63.	775.	842.	700.	811.	26990.	2778.	29768.	10.0	.295	2693.
76.0	2.0	2.5	.504	60.	626.	469.	68.	63.	775.	842.	700.	811.	26393.	2843.	29236.	9.9	.295	2677.
77.0	2.0	2.4	.493	60.	627.	473.	63.	63.	775.	842.	700.	811.	25799.	2909.	28707.	9.9	.295	2666.
78.0	2.0	2.4	.482	60.	628.	477.	63.	63.	776.	843.	700.	811.	25206.	2973.	28180.	9.8	.295	2657.
79.0	2.0	2.4	.470	60.	630.	481.	63.	63.	776.	843.	700.	811.	24617.	3038.	27655.	9.8	.295	2647.
80.0	2.0	2.4	.459	60.	631.	485.	63.	63.	776.	843.	700.	811.	24029.	3103.	27131.	9.8	.295	2637.
81.0	2.0	2.4	.448	60.	632.	488.	63.	63.	777.	843.	700.	811.	23443.	3167.	26610.	9.7	.295	2625.



tank model with jacket.OUT

82.0	2.0	2.4	437	60.	633.	491.	63.	777.	844.	700.	811.	22861.	3231.	26091.	9.7	.295	2614.
83.0	2.0	2.4	426	60.	634.	495.	63.	777.	844.	700.	811.	22281.	3294.	25575.	9.6	.295	2602.
84.0	2.0	2.4	415	60.	635.	498.	63.	778.	844.	700.	811.	21703.	3358.	25061.	9.6	.295	2589.
85.0	2.0	2.3	404	60.	635.	500.	63.	778.	844.	700.	811.	21129.	3421.	24549.	9.5	.295	2576.
86.0	2.0	2.3	393	60.	636.	503.	63.	778.	845.	700.	811.	20557.	3483.	24041.	9.5	.295	2562.
87.0	2.0	2.3	382	60.	637.	506.	63.	778.	845.	700.	811.	19989.	3546.	23535.	9.4	.295	2548.
88.0	2.0	2.3	371	60.	638.	508.	63.	779.	845.	700.	811.	19424.	3608.	23032.	9.4	.295	2533.
89.0	2.0	2.3	360	60.	639.	511.	63.	779.	845.	700.	811.	18862.	3669.	22531.	9.3	.295	2518.
90.0	2.0	2.3	350	60.	640.	513.	63.	779.	845.	700.	811.	18304.	3730.	22034.	9.3	.295	2502.
91.0	2.0	2.3	339	60.	641.	516.	63.	780.	846.	700.	811.	17749.	3791.	21540.	9.2	.295	2486.
92.0	2.0	2.3	329	60.	642.	518.	63.	780.	846.	700.	811.	17198.	3852.	21049.	9.2	.295	2469.
93.0	2.0	2.2	318	60.	643.	520.	63.	780.	846.	700.	811.	16650.	3912.	20562.	9.1	.295	2452.
94.0	2.0	2.2	308	60.	644.	523.	63.	780.	846.	700.	811.	16107.	3971.	20078.	9.0	.295	2434.
95.0	2.0	2.2	297	60.	644.	525.	63.	781.	846.	700.	811.	15567.	4031.	19598.	9.0	.295	2417.
96.0	2.0	2.2	287	60.	645.	527.	63.	781.	846.	700.	811.	15032.	4089.	19121.	8.9	.295	2399.
97.0	2.0	2.2	277	60.	646.	529.	63.	781.	847.	700.	811.	14500.	4148.	18648.	8.8	.295	2380.
98.0	2.0	2.2	267	60.	647.	531.	63.	782.	847.	700.	811.	13973.	4205.	18178.	8.7	.295	2359.
99.0	2.0	2.2	257	60.	648.	534.	63.	782.	847.	700.	811.	13450.	4263.	17713.	8.7	.295	2340.
100.0	2.0	2.2	247	60.	649.	536.	63.	782.	847.	700.	811.	12932.	4320.	17252.	8.6	.295	2320.
101.0	2.0	2.1	237	60.	650.	538.	63.	782.	847.	700.	811.	12418.	4376.	16794.	8.5	.295	2297.
102.0	2.0	2.1	227	60.	651.	540.	63.	783.	847.	700.	811.	11910.	4432.	16341.	8.4	.295	2277.
103.0	2.0	2.1	218	60.	652.	542.	63.	783.	848.	700.	811.	11406.	4487.	15893.	8.4	.295	2254.
104.0	2.0	2.1	208	60.	653.	544.	63.	783.	848.	700.	811.	10907.	4542.	15448.	8.3	.295	2231.
105.0	2.0	2.1	199	60.	654.	547.	63.	784.	848.	700.	811.	10413.	4596.	15009.	8.2	.295	2207.
106.0	2.0	2.1	190	60.	655.	549.	63.	784.	848.	700.	811.	9925.	4649.	14574.	8.1	.295	2183.

birk model

106.0 655.4 .9 1.386

birk 2nd model

106.0 655.4 .9 1.386

107.0	2.0	2.1	180	60.	657.	551.	63.	785.	848.	700.	811.	9442.	4702.	14144.	8.0	.295	2158.
108.0	2.0	2.0	171	60.	658.	553.	63.	785.	848.	700.	811.	8965.	4755.	13720.	7.9	.295	2132.
109.0	2.0	2.0	162	60.	659.	556.	63.	785.	849.	700.	811.	8494.	4806.	13300.	7.8	.295	2105.
110.0	2.0	2.0	153	60.	660.	558.	63.	786.	849.	700.	811.	8029.	4857.	12886.	7.7	.295	2077.
111.0	2.0	2.0	145	60.	661.	561.	63.	786.	849.	700.	811.	7570.	4908.	12477.	7.6	.295	2048.
112.0	2.0	2.0	136	60.	663.	563.	63.	787.	849.	700.	811.	7117.	4957.	12075.	7.5	.295	2018.
113.0	2.0	2.0	127	60.	664.	566.	63.	787.	849.	700.	811.	6672.	5006.	11678.	7.4	.295	1987.
114.0	2.0	1.9	119	60.	665.	568.	63.	787.	849.	700.	811.	6233.	5054.	11287.	7.2	.295	1955.
115.0	2.0	1.9	111	60.	667.	571.	63.	788.	850.	700.	811.	5802.	5101.	10903.	7.1	.295	1922.
116.0	2.0	1.9	103	60.	668.	573.	63.	788.	850.	700.	811.	5379.	5148.	10526.	7.0	.295	1885.

117.0	2.0	1.9	.095	60.	670.	576.	63.	63.	789.	850.	700.	811.	4963.	5193.	10156.	6.9	.295	1848.
118.0	2.0	1.9	.087	60.	672.	579.	63.	63.	789.	850.	700.	811.	4556.	5238.	9794.	6.7	.295	1809.
119.0	2.0	1.8	.079	60.	673.	582.	63.	63.	790.	850.	700.	811.	4158.	5282.	9440.	6.6	.295	1768.
120.0	2.0	1.8	.072	60.	675.	585.	63.	63.	791.	851.	700.	811.	3769.	5324.	9093.	6.4	.295	1725.
121.0	2.0	1.8	.065	60.	677.	588.	63.	63.	791.	851.	700.	811.	3390.	5366.	8756.	6.2	.295	1680.
122.0	2.0	1.8	.058	60.	679.	591.	63.	63.	792.	851.	700.	811.	3022.	5406.	8428.	6.0	.295	1631.
123.0	2.0	1.7	.051	60.	681.	595.	63.	63.	792.	851.	700.	811.	2665.	5445.	8111.	5.8	.295	1577.
124.0	2.0	1.7	.044	60.	683.	598.	63.	63.	793.	852.	700.	811.	2320.	5483.	7804.	5.6	.295	1521.
Larson Miller model																		
124.8	2.0	1.7	.038	60.	685.	602.	63.	63.	794.	852.	700.	811.	1989.	5520.	7508.	5.4	.295	1459.
125.0	2.0	1.6	.032	60.	688.	606.	63.	63.	795.	852.	700.	811.	1671.	5554.	7226.	5.2	.295	1392.
126.0	2.0	1.6	.026	60.	690.	609.	63.	63.	796.	852.	700.	811.	1370.	5587.	6957.	4.9	.295	1317.
127.0	2.0	1.6	.021	60.	693.	614.	63.	63.	797.	853.	700.	811.	1086.	5619.	6704.	4.6	.295	1234.
128.1	2.0	1.6	.020	60.	693.	614.	63.	63.	797.	853.	700.	811.	1049.	5623.	6704.	4.5	.295	1222.



TMID effect of defect position

input data

propane  
fire temp (deg C) = 816.000000  
fire emissivity = 1.000000  
fire conv h (W/m^2K) = 0.000000E+00  
fire exposure frac = 1.000000  
tank D (m) = 3.000000  
tank L/D = 5.770000  
tank volume (m^3) = 122.357100  
tank initial fill fraction = 9.000000E-01  
wall thick (mm) = 17.500000  
PRV operating P (MPa) = 2.000000  
surface emissivity = 9.000000E-01  
lading initial temp (deg C) = 16.000000  
critical wall temp (deg C) = 427.000000  
jacket gap (mm) = 13.000000  
insul defect length (m) = 17.310000  
angle to defect top (deg) = 20.000000  
angle to defect bot (deg) = 110.000000  
constant insulation conductance (W/m^2 K) = 22.700000

time	press	pbst	fill	tlad	twvd	twvi	twli	twld	tjvd	tjvi	tjld	tjli	mliq	mvap	mtot	mdot	kins	qdottot
(min)	(MPa)	(MPa)	C	C	C	C	C	C	C	C	C	C	kg	kg	kg	kg/s	W/mK	kW
1.0	.7	6.4	.900	16.	19.	20.	17.	17.	394.	389.	394.	389.	55703.	197.	55900.	.0	.295	874.
2.0	.7	6.4	.902	17.	37.	31.	21.	19.	591.	619.	591.	618.	55699.	197.	55896.	.0	.295	1922.
3.0	.7	6.4	.904	18.	67.	46.	24.	20.	642.	712.	641.	710.	55696.	197.	55893.	.0	.295	2428.
4.0	.7	6.4	.907	19.	99.	60.	25.	22.	652.	741.	651.	738.	55689.	197.	55886.	.0	.295	2578.
5.0	.7	6.4	.909	20.	131.	75.	26.	23.	655.	749.	652.	745.	55684.	196.	55880.	.0	.295	2621.
6.0	.8	6.4	.913	21.	163.	90.	27.	24.	656.	752.	653.	747.	55692.	195.	55887.	.0	.295	2641.
7.0	.8	6.3	.916	22.	194.	104.	28.	25.	658.	754.	653.	747.	55703.	193.	55896.	.0	.295	2662.
8.0	.8	6.3	.919	23.	225.	118.	30.	26.	660.	755.	653.	748.	55712.	191.	55903.	.0	.295	2683.
9.0	.8	6.2	.922	24.	254.	132.	31.	27.	662.	757.	653.	748.	55718.	188.	55907.	.0	.295	2705.

10.0	.9	6.1	.925	25.	282.	145.	32.	t38k	668e175gth65ack2480U#5719.	186.	55905.	.0	.295	2731.				
11.0	.9	6.0	.928	26.	308.	157.	33.	29.	667.	759.	653.	748.	55716.	183.	55899.	.0	.295	2753.
12.0	.9	5.9	.932	27.	333.	170.	34.	30.	670.	760.	653.	748.	55709.	179.	55888.	.0	.295	2776.
13.0	.9	5.7	.935	28.	357.	182.	35.	31.	674.	761.	653.	748.	55704.	175.	55879.	.0	.295	2800.
14.0	1.0	5.5	.938	29.	379.	193.	36.	32.	677.	762.	653.	748.	55699.	171.	55870.	.0	.295	2822.
15.0	1.0	5.3	.942	30.	399.	204.	37.	34.	680.	764.	653.	748.	55695.	166.	55861.	.0	.295	2852.
16.0	1.0	5.1	.945	32.	418.	215.	38.	35.	683.	765.	653.	748.	55686.	161.	55847.	.0	.295	2876.
critical wall temperature reached																		
17.0	1.1	5.1	.949	33.	434.	225.	39.	36.	687.	765.	653.	749.	55684.	155.	55839.	.0	.295	2898.
18.0	1.1	4.9	.952	34.	450.	235.	40.	37.	690.	766.	653.	749.	55679.	148.	55827.	.0	.295	2925.
19.0	1.1	4.7	.956	35.	463.	245.	42.	38.	693.	767.	653.	749.	55679.	139.	55818.	.0	.295	2946.
20.0	1.2	4.5	.961	36.	475.	254.	43.	39.	695.	768.	653.	749.	55706.	128.	55834.	.0	.295	2970.
21.0	1.2	4.4	.966	37.	486.	263.	44.	40.	698.	769.	653.	749.	55731.	116.	55847.	.0	.295	3001.
22.0	1.2	4.2	.970	39.	496.	271.	45.	42.	700.	770.	653.	749.	55754.	103.	55857.	.0	.295	3027.
23.0	1.3	4.1	.975	40.	504.	279.	46.	43.	702.	770.	653.	749.	55772.	90.	55861.	.0	.295	3060.
24.0	1.3	4.0	.980	41.	511.	286.	48.	44.	704.	771.	653.	749.	55784.	75.	55859.	.0	.295	3091.
25.0	1.3	3.9	.984	42.	518.	293.	49.	45.	706.	772.	653.	749.	55795.	59.	55854.	.0	.295	3119.
26.0	1.4	3.9	.989	43.	523.	300.	50.	46.	707.	772.	653.	750.	55797.	43.	55840.	.0	.295	3158.
27.0	1.4	6.4	.994	45.	85.	306.	51.	48.	679.	773.	653.	750.	55796.	26.	55822.	.0	.295	3205.
28.0	1.5	6.4	.999	46.	53.	169.	52.	49.	657.	772.	653.	750.	55806.	5.	55811.	.0	.295	3337.
29.0	1.5	6.41.000	47.	54.	51.		54.	50.	654.	756.	653.	750.	55585.	0.	55585.	4.7	.295	3338.
30.0	1.5	6.41.000	48.	55.	51.		55.	51.	653.	752.	653.	750.	55300.	0.	55300.	5.2	.295	3334.
31.0	1.6	6.41.000	50.	56.	53.		56.	53.	653.	750.	653.	750.	54989.	0.	54989.	5.2	.295	3332.
32.0	1.6	6.41.000	51.	57.	54.		57.	54.	653.	750.	653.	750.	54682.	0.	54682.	5.1	.295	3328.
33.0	1.7	6.41.000	52.	59.	55.		59.	55.	653.	750.	653.	750.	54377.	0.	54377.	5.3	.295	3324.
34.0	1.7	6.41.000	53.	60.	56.		60.	56.	653.	750.	653.	750.	54061.	0.	54061.	5.2	.295	3321.
35.0	1.8	6.41.000	55.	61.	57.		61.	57.	653.	751.	653.	751.	53747.	0.	53747.	5.2	.295	3316.
36.0	1.8	6.41.000	56.	62.	59.		62.	59.	653.	751.	653.	751.	53436.	0.	53436.	5.2	.295	3312.
37.0	1.9	6.41.000	57.	64.	60.		64.	60.	653.	751.	653.	751.	53099.	0.	53099.	5.6	.295	3308.
38.0	1.9	6.41.000	58.	65.	61.		65.	61.	653.	751.	653.	751.	52765.	0.	52765.	5.6	.295	3303.
39.0	2.0	6.41.000	60.	66.	62.		66.	63.	654.	751.	654.	751.	52433.	0.	52433.	5.5	.295	3298.
40.0	2.0	6.4	.990	60.	69.	71.	67.	63.	654.	751.	654.	751.	51821.	55.	51876.	12.0	.295	3235.
41.0	2.0	6.4	.977	60.	102.	86.	67.	63.	654.	752.	654.	751.	51119.	132.	51251.	11.4	.295	3084.
42.0	2.0	6.4	.964	60.	135.	101.	67.	63.	655.	754.	654.	751.	50447.	206.	50652.	11.0	.295	2974.
43.0	2.0	6.4	.951	60.	167.	115.	67.	63.	657.	755.	654.	751.	49793.	277.	50071.	10.7	.295	2898.
44.0	2.0	6.3	.939	60.	198.	129.	67.	63.	658.	756.	654.	751.	49156.	347.	49503.	10.5	.295	2838.
45.0	2.0	6.3	.927	60.	228.	142.	67.	63.	660.	758.	654.	751.	48530.	416.	48946.	10.3	.295	2789.
46.0	2.0	6.2	.916	60.	258.	155.	67.	63.	663.	759.	654.	751.	47914.	483.	48398.	10.2	.295	2747.
47.0	2.0	6.1	.904	60.	286.	167.	67.	63.	665.	760.	654.	751.	47307.	550.	47857.	10.1	.295	2716.
48.0	2.0	6.0	.892	60.	312.	179.	67.	63.	668.	761.	654.	751.	46706.	616.	47322.	10.0	.295	2687.
49.0	2.0	5.8	.881	60.	337.	191.	67.	63.	671.	762.	654.	751.	46111.	681.	46792.	9.9	.295	2665.
50.0	2.0	5.7	.870	60.	361.	203.	67.	63.	674.	763.	654.	751.	45521.	746.	46267.	9.8	.295	2646.

52.0 2.0 5.3 .847 60. 403. 225. 67. 63. 681. 765. 654. 751. 44350. 810. 45224. 9.7 .295 2621. 9.7 .295 2621.  
53.0 2.0 5.1 .836 60. 422. 236. 67. 63. 684. 766. 654. 751. 43768. 938. 44706. 9.7 .295 2614. 9.7 .295 2614.  
54.0 2.0 5.0 .825 60. 439. 246. 67. 63. 687. 767. 654. 751. 43187. 1002. 44189. 9.7 .295 2605. 9.7 .295 2605.  
55.0 2.0 4.8 .814 60. 454. 256. 67. 63. 691. 768. 654. 751. 42608. 1065. 43673. 9.6 .295 2600. 9.6 .295 2600.  
56.0 2.0 4.6 .803 60. 468. 266. 67. 63. 694. 769. 654. 751. 42030. 1129. 43158. 9.6 .295 2599. 9.6 .295 2599.  
57.0 2.0 4.4 .792 60. 481. 275. 67. 63. 696. 770. 654. 751. 41452. 1192. 42644. 9.6 .295 2595. 9.6 .295 2595.  
58.0 2.0 4.3 .781 60. 492. 284. 67. 63. 699. 771. 654. 751. 40875. 1255. 42130. 9.6 .295 2594. 9.6 .295 2594.  
59.0 2.0 4.1 .770 60. 502. 293. 67. 63. 702. 772. 654. 751. 40298. 1319. 41617. 9.6 .295 2592. 9.6 .295 2592.  
60.0 2.0 4.0 .759 60. 510. 302. 67. 63. 704. 772. 654. 751. 39722. 1382. 41104. 9.6 .295 2590. 9.6 .295 2590.  
61.0 2.0 3.9 .748 60. 518. 310. 67. 63. 706. 773. 654. 751. 39146. 1455. 40591. 9.6 .295 2587. 9.6 .295 2587.  
62.0 2.0 3.8 .737 60. 525. 318. 67. 63. 708. 774. 654. 751. 38571. 1508. 40079. 9.6 .295 2585. 9.6 .295 2585.  
63.0 2.0 3.7 .726 60. 531. 326. 67. 63. 709. 775. 654. 751. 37997. 1571. 39568. 9.6 .295 2581. 9.6 .295 2581.  
64.0 2.0 3.7 .715 60. 537. 333. 67. 63. 711. 775. 654. 751. 37423. 1634. 39057. 9.6 .295 2577. 9.6 .295 2577.  
65.0 2.0 3.6 .704 60. 541. 341. 67. 63. 712. 776. 654. 751. 36850. 1697. 38546. 9.5 .295 2575. 9.5 .295 2575.  
66.0 2.0 3.6 .693 60. 546. 348. 67. 63. 713. 777. 654. 751. 36278. 1759. 38037. 9.5 .295 2569. 9.5 .295 2569.  
67.0 2.0 3.5 .682 60. 549. 354. 67. 63. 714. 777. 654. 751. 35706. 1822. 37529. 9.5 .295 2565. 9.5 .295 2565.  
68.0 2.0 3.5 .671 60. 553. 361. 67. 63. 715. 778. 654. 751. 35136. 1885. 37021. 9.5 .295 2561. 9.5 .295 2561.  
69.0 2.0 3.4 .660 60. 556. 367. 67. 63. 716. 778. 654. 751. 34568. 1947. 36515. 9.5 .295 2553. 9.5 .295 2553.  
70.0 2.0 3.4 .650 60. 558. 373. 67. 63. 717. 779. 654. 751. 34000. 2009. 36009. 9.4 .295 2547. 9.4 .295 2547.  
71.0 2.0 3.3 .639 60. 561. 379. 67. 63. 718. 779. 654. 751. 33434. 2071. 35505. 9.4 .295 2541. 9.4 .295 2541.  
72.0 2.0 3.3 .628 60. 563. 384. 67. 63. 719. 780. 654. 751. 32870. 2133. 35003. 9.4 .295 2534. 9.4 .295 2534.  
73.0 2.0 3.3 .617 60. 565. 390. 67. 63. 719. 780. 654. 751. 32307. 2195. 34502. 9.4 .295 2527. 9.4 .295 2527.  
74.0 2.0 3.3 .607 60. 567. 395. 67. 63. 720. 781. 654. 751. 31746. 2256. 34002. 9.3 .295 2519. 9.3 .295 2519.  
75.0 2.0 3.2 .596 60. 569. 400. 67. 63. 720. 781. 654. 751. 31186. 2318. 33504. 9.3 .295 2510. 9.3 .295 2510.  
76.0 2.0 3.2 .585 60. 570. 404. 67. 63. 721. 782. 654. 751. 30629. 2379. 33008. 9.3 .295 2501. 9.3 .295 2501.  
AFTAC model with fos = 1.600000  
76.9 2.0 3.2 .576 60. 572. 408. 67. 63. 721. 782. 654. 751. 30147. 2432. 33008. 9.2 .295 2493. 9.2 .295 2493.  
77.0 2.0 3.2 .575 60. 572. 409. 67. 63. 721. 782. 654. 751. 30073. 2440. 32513. 9.2 .295 2492. 9.2 .295 2492.  
78.0 2.0 3.2 .564 60. 573. 413. 67. 63. 722. 782. 654. 751. 29520. 2500. 32021. 9.2 .295 2481. 9.2 .295 2481.  
79.0 2.0 3.2 .553 60. 575. 417. 67. 63. 722. 783. 654. 751. 28969. 2561. 31530. 9.2 .295 2473. 9.2 .295 2473.  
80.0 2.0 3.1 .543 60. 576. 421. 67. 63. 722. 783. 654. 751. 28420. 2621. 31041. 9.1 .295 2463. 9.1 .295 2463.  
81.0 2.0 3.1 .533 60. 577. 425. 67. 63. 723. 783. 654. 751. 27873. 2681. 30554. 9.1 .295 2452. 9.1 .295 2452.  
82.0 2.0 3.1 .522 60. 578. 429. 67. 63. 723. 784. 654. 751. 27329. 2741. 30070. 9.1 .295 2441. 9.1 .295 2441.  
83.0 2.0 3.1 .512 60. 579. 432. 67. 63. 723. 784. 654. 751. 26787. 2800. 29588. 9.0 .295 2430. 9.0 .295 2430.  
84.0 2.0 3.1 .502 60. 581. 436. 67. 63. 724. 784. 654. 751. 26248. 2859. 29107. 9.0 .295 2418. 9.0 .295 2418.  
85.0 2.0 3.1 .491 60. 582. 439. 67. 63. 724. 785. 654. 751. 25712. 2918. 28630. 8.9 .295 2406. 8.9 .295 2406.  
86.0 2.0 3.0 .481 60. 583. 442. 67. 63. 725. 785. 654. 751. 25178. 2977. 28154. 8.9 .295 2394. 8.9 .295 2394.  
87.0 2.0 3.0 .471 60. 584. 446. 67. 63. 725. 785. 654. 751. 24646. 3035. 27681. 8.8 .295 2380. 8.8 .295 2380.  
88.0 2.0 3.0 .461 60. 585. 449. 67. 63. 725. 786. 654. 751. 24118. 3093. 27211. 8.8 .295 2369. 8.8 .295 2369.  
89.0 2.0 3.0 .451 60. 586. 451. 67. 63. 725. 786. 654. 751. 23593. 3151. 26743. 8.7 .295 2355. 8.7 .295 2355.  
90.0 2.0 3.0 .441 60. 587. 454. 67. 63. 726. 786. 654. 751. 23070. 3208. 26278. 8.7 .295 2342. 8.7 .295 2342.



91.0	2.0	3.0	431	60.	598.	457.	67.	task	Model706th65Acke2510U22551.	3265.	25816.	8.6	.295	2328.
92.0	2.0	3.0	421	60.	589.	460.	67.	63.	726. 787. 654. 751. 22034.	3321.	25356.	8.6	.295	2314.
93.0	2.0	2.9	411	60.	590.	462.	67.	63.	727. 787. 654. 751. 21521.	3378.	24899.	8.5	.295	2299.
94.0	2.0	2.9	401	60.	591.	465.	67.	63.	727. 787. 654. 751. 21011.	3434.	24445.	8.5	.295	2285.
95.0	2.0	2.9	392	60.	592.	468.	67.	63.	727. 787. 654. 751. 20505.	3489.	23994.	8.4	.295	2270.
96.0	2.0	2.9	382	60.	593.	470.	67.	63.	728. 787. 654. 751. 20001.	3544.	23546.	8.4	.295	2255.
97.0	2.0	2.9	373	60.	594.	473.	67.	63.	728. 788. 654. 751. 19501.	3599.	23101.	8.3	.295	2238.
98.0	2.0	2.9	363	60.	595.	475.	67.	63.	728. 788. 654. 751. 19005.	3654.	22659.	8.2	.295	2224.
99.0	2.0	2.9	354	60.	596.	477.	67.	63.	729. 788. 654. 751. 18512.	3708.	22220.	8.2	.295	2207.
100.0	2.0	2.9	344	60.	597.	480.	67.	63.	729. 788. 654. 751. 18023.	3761.	21784.	8.1	.295	2191.
101.0	2.0	2.8	335	60.	598.	482.	67.	63.	729. 788. 654. 751. 17537.	3815.	21352.	8.1	.295	2175.
102.0	2.0	2.8	326	60.	599.	484.	67.	63.	730. 789. 654. 751. 17056.	3867.	20923.	8.0	.295	2157.
103.0	2.0	2.8	317	60.	601.	487.	67.	63.	730. 789. 654. 751. 16578.	3920.	20497.	7.9	.295	2140.
104.0	2.0	2.8	308	60.	602.	489.	67.	63.	730. 789. 654. 751. 16104.	3972.	20075.	7.9	.295	2122.
105.0	2.0	2.8	299	60.	603.	491.	67.	63.	731. 789. 654. 751. 15633.	4023.	19657.	7.8	.295	2104.
106.0	2.0	2.8	290	60.	604.	493.	67.	63.	731. 789. 654. 751. 15167.	4074.	19242.	7.7	.295	2086.
107.0	2.0	2.8	281	60.	605.	496.	63.	63.	731. 790. 653. 751. 14705.	4125.	18830.	7.7	.295	2071.
108.0	2.0	2.7	272	60.	606.	498.	63.	63.	732. 790. 653. 751. 14246.	4176.	18421.	7.6	.295	2057.
109.0	2.0	2.7	263	60.	607.	500.	63.	63.	732. 790. 653. 751. 13790.	4226.	18015.	7.6	.295	2044.
110.0	2.0	2.7	255	60.	608.	502.	63.	63.	732. 790. 653. 751. 13337.	4275.	17612.	7.5	.295	2029.
111.0	2.0	2.7	246	60.	609.	504.	63.	63.	733. 790. 653. 751. 12887.	4325.	17211.	7.5	.295	2015.
112.0	2.0	2.7	238	60.	610.	506.	63.	63.	733. 791. 653. 751. 12440.	4374.	16814.	7.4	.295	2000.
113.0	2.0	2.7	229	60.	611.	508.	63.	63.	733. 791. 653. 751. 11997.	4422.	16419.	7.4	.295	1983.
114.0	2.0	2.7	221	60.	612.	510.	63.	63.	734. 791. 653. 751. 11558.	4470.	16028.	7.3	.295	1968.
115.0	2.0	2.6	212	60.	613.	512.	63.	63.	734. 791. 653. 751. 11122.	4518.	15640.	7.2	.295	1951.
116.0	2.0	2.6	204	60.	614.	514.	63.	63.	734. 791. 653. 751. 10690.	4566.	15255.	7.2	.295	1934.
117.0	2.0	2.6	196	60.	615.	516.	63.	63.	735. 791. 653. 751. 10262.	4612.	14874.	7.1	.295	1916.
118.0	2.0	2.6	188	60.	616.	518.	63.	63.	735. 792. 653. 751. 9838.	4659.	14497.	7.0	.295	1897.
119.0	2.0	2.6	180	60.	617.	520.	63.	63.	735. 792. 653. 751. 9418.	4705.	14123.	7.0	.295	1878.
120.0	2.0	2.6	172	60.	618.	522.	63.	63.	736. 792. 653. 751. 9002.	4751.	13753.	6.9	.295	1859.
121.0	2.0	2.6	164	60.	619.	525.	63.	63.	736. 792. 653. 751. 8591.	4796.	13386.	6.8	.295	1839.
122.0	2.0	2.5	156	60.	620.	527.	63.	63.	736. 792. 653. 751. 8184.	4840.	13024.	6.7	.295	1818.
123.0	2.0	2.5	149	60.	621.	529.	63.	63.	737. 792. 653. 751. 7782.	4884.	12666.	6.7	.295	1796.
124.0	2.0	2.5	141	60.	622.	531.	63.	63.	737. 793. 653. 751. 7385.	4928.	12313.	6.6	.295	1773.
125.0	2.0	2.5	134	60.	624.	533.	63.	63.	737. 793. 653. 751. 6993.	4971.	11964.	6.5	.295	1751.
126.0	2.0	2.5	126	60.	625.	535.	63.	63.	738. 793. 653. 751. 6606.	5013.	11619.	6.4	.295	1727.
127.0	2.0	2.5	119	60.	626.	537.	63.	63.	738. 793. 653. 751. 6224.	5055.	11280.	6.3	.295	1702.
128.0	2.0	2.4	112	60.	627.	539.	63.	63.	739. 793. 653. 751. 5848.	5096.	10945.	6.2	.295	1676.
129.0	2.0	2.4	105	60.	628.	542.	63.	63.	739. 794. 653. 751. 5478.	5137.	10615.	6.1	.295	1650.
130.0	2.0	2.4	098	60.	630.	544.	63.	63.	740. 794. 653. 751. 5114.	5177.	10291.	6.0	.295	1622.
131.0	2.0	2.4	091	60.	631.	546.	63.	63.	740. 794. 653. 751. 4757.	5216.	9973.	5.9	.295	1593.
132.0	2.0	2.4	084	60.	632.	549.	63.	63.	740. 794. 653. 751. 4406.	5255.	9660.	5.8	.295	1563.

133.0	2.0	2.4	670	60	634	351	63	634	791	532	3292	9354	5.7	295	1331.
134.0	2.0	2.3	.071	60	635	554	63	63	741	795	653	751	3724	5329	9054
135.0	2.0	2.3	.065	60	637	557	63	63	742	795	653	751	3395	5365	8761
136.0	2.0	2.3	.059	60	639	559	63	63	742	795	653	751	3074	5401	8475
137.0	2.0	2.3	.053	60	640	562	63	63	743	795	653	751	2761	5435	8196
138.0	2.0	2.2	.047	60	642	565	63	63	744	795	653	751	2458	5468	7926
139.0	2.0	2.2	.041	60	644	568	63	63	744	796	653	751	2164	5501	7664
140.0	2.0	2.2	.036	60	646	571	63	63	745	796	653	751	1880	5532	7412
141.0	2.0	2.2	.031	60	648	574	63	63	746	796	653	751	1608	5561	7169
142.0	2.0	2.1	.026	60	650	577	63	63	746	796	653	751	1348	5590	6938
143.0	2.0	2.1	.021	60	652	581	63	63	747	797	653	751	1101	5617	6718
143.2	2.0	2.1	.020	60	653	582	63	63	747	797	653	751	1049	5623	6718



Tank Model with Insulation Defects (TMID v1.0)

input data

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propane
fire temp (deg C)      =      816.000000
fire emissivity         =      1.000000
fire conv h (W/m^2K)    =      0.000000E+00
fire exposure frac      =      1.000000
tank D (m)              =      3.000000
tank L/D                =      5.770000
tank volume (m^3)       =      122.357100
tank initial fill fraction =      9.000000E-01
wall thick (mm)         =      17.500000
PRV operating P (MPa)   =      2.000000
surface emissivity      =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)         =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      40.000000
angle to defect bot (deg) =      130.000000
constant insulation conductance (W/m^2 K)=      22.700000
  
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time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twvd C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.900	16.	19.	20.	17.	17.	394.	389.	394.	389.	55703.	197.	55900.	.0	.295	870.
2.0	.7	6.4	.902	17.	37.	31.	21.	19.	591.	619.	591.	618.	55699.	197.	55896.	.0	.295	2011.
3.0	.7	6.4	.904	18.	67.	46.	24.	21.	642.	712.	641.	710.	55695.	197.	55892.	.0	.295	2570.
4.0	.7	6.4	.907	19.	99.	60.	25.	22.	652.	741.	651.	738.	55697.	197.	55894.	.0	.295	2725.
5.0	.7	6.4	.910	20.	131.	75.	26.	23.	655.	749.	652.	745.	55691.	196.	55887.	.0	.295	2773.
6.0	.8	6.4	.913	21.	163.	90.	28.	24.	656.	752.	653.	747.	55686.	195.	55881.	.0	.295	2796.

7.0	.8	6.3	.916	22.	194.	104.	29.	25.	658.	754.	653.	747.	55679.	194.	55873.	.0	.295	2810.
8.0	.8	6.3	.919	23.	225.	118.	30.	26.	660.	755.	653.	748.	55671.	192.	55863.	.0	.295	2827.
9.0	.8	6.2	.922	24.	254.	131.	31.	27.	662.	757.	653.	748.	55661.	190.	55851.	.0	.295	2843.
10.0	.9	6.1	.925	25.	282.	144.	32.	28.	665.	758.	653.	748.	55659.	188.	55846.	.0	.295	2861.
11.0	.9	6.0	.929	26.	308.	157.	33.	30.	667.	759.	653.	748.	55654.	184.	55838.	.0	.295	2878.
12.0	.9	5.9	.932	28.	333.	169.	34.	31.	670.	760.	653.	748.	55646.	180.	55827.	.0	.295	2898.
13.0	.9	6.4	.935	29.	123.	181.	35.	32.	668.	761.	653.	748.	55637.	176.	55814.	.0	.295	2911.
14.0	1.0	6.4	.939	30.	37.	192.	37.	33.	656.	762.	653.	748.	55632.	172.	55803.	.0	.295	2923.
15.0	1.0	6.4	.942	31.	38.	203.	38.	34.	653.	763.	653.	748.	55628.	166.	55794.	.0	.295	2937.
16.0	1.0	6.4	.946	32.	39.	213.	39.	35.	653.	764.	653.	748.	55645.	159.	55804.	.0	.295	2947.
17.0	1.1	6.4	.951	33.	40.	223.	40.	36.	653.	765.	653.	749.	55668.	151.	55819.	.0	.295	2964.
18.0	1.1	6.4	.955	35.	41.	233.	41.	38.	653.	766.	653.	749.	55690.	141.	55832.	.0	.295	2985.
19.0	1.1	6.4	.960	36.	42.	242.	42.	39.	653.	767.	653.	749.	55709.	131.	55840.	.0	.295	3006.
20.0	1.2	6.4	.964	37.	44.	251.	44.	40.	653.	768.	653.	749.	55724.	120.	55844.	.0	.295	3024.
21.0	1.2	6.4	.969	38.	45.	260.	45.	41.	653.	769.	653.	749.	55743.	107.	55851.	.0	.295	3048.
22.0	1.3	6.4	.973	39.	46.	268.	46.	42.	653.	769.	653.	749.	55758.	94.	55852.	.0	.295	3064.
23.0	1.3	6.4	.978	41.	47.	275.	47.	44.	653.	770.	653.	749.	55767.	81.	55848.	.0	.295	3089.
24.0	1.3	6.4	.983	42.	48.	283.	48.	45.	653.	771.	653.	749.	55778.	65.	55843.	.0	.295	3112.
25.0	1.4	6.4	.987	43.	50.	290.	50.	46.	653.	771.	653.	749.	55782.	49.	55831.	.0	.295	3145.
26.0	1.4	6.4	.992	44.	51.	296.	51.	47.	653.	772.	653.	750.	55780.	32.	55812.	.0	.295	3184.
27.0	1.4	6.4	.997	45.	52.	302.	52.	48.	653.	773.	653.	750.	55784.	13.	55797.	.0	.295	3247.
28.0	1.5	6.41	.000	47.	53.	54.	53.	50.	653.	760.	653.	750.	55671.	0.	55671.	4.8	.295	3339.
29.0	1.5	6.41	.000	48.	54.	51.	55.	51.	653.	752.	653.	750.	55388.	0.	55388.	4.7	.295	3335.
30.0	1.6	6.41	.000	49.	56.	52.	56.	52.	653.	751.	653.	750.	55084.	0.	55084.	5.2	.295	3333.
31.0	1.6	6.41	.000	50.	57.	53.	57.	53.	653.	750.	653.	750.	54775.	0.	54775.	5.1	.295	3330.
32.0	1.7	6.41	.000	52.	58.	55.	58.	55.	653.	750.	653.	750.	54470.	0.	54470.	5.1	.295	3326.
33.0	1.7	6.41	.000	53.	59.	56.	60.	56.	653.	750.	653.	750.	54157.	0.	54157.	5.3	.295	3322.
34.0	1.8	6.41	.000	54.	61.	57.	61.	57.	653.	751.	653.	751.	53843.	0.	53843.	5.2	.295	3318.
35.0	1.8	6.41	.000	55.	62.	58.	62.	58.	653.	751.	653.	751.	53530.	0.	53530.	5.2	.295	3313.
36.0	1.9	6.41	.000	57.	63.	60.	63.	60.	653.	751.	653.	751.	53201.	0.	53201.	5.6	.295	3309.
37.0	1.9	6.41	.000	58.	64.	61.	65.	61.	653.	751.	653.	751.	52867.	0.	52867.	5.5	.295	3306.
38.0	2.0	6.41	.000	59.	66.	62.	66.	62.	654.	751.	654.	751.	52534.	0.	52534.	5.5	.295	3300.
39.0	2.0	6.4	.994	60.	67.	67.	67.	63.	654.	751.	654.	751.	52040.	31.	52071.	12.2	.295	3283.
40.0	2.0	6.4	.981	60.	67.	82.	67.	63.	654.	752.	654.	751.	51324.	110.	51434.	11.7	.295	3156.
41.0	2.0	6.4	.967	60.	67.	96.	67.	63.	654.	753.	654.	751.	50629.	186.	50815.	11.4	.295	3087.
42.0	2.0	6.4	.954	60.	67.	111.	67.	63.	654.	755.	654.	751.	49948.	260.	50209.	11.2	.295	3032.
43.0	2.0	6.4	.942	60.	67.	124.	67.	63.	654.	756.	654.	751.	49278.	334.	49612.	11.1	.295	2993.
44.0	2.0	6.4	.929	60.	81.	138.	67.	63.	654.	757.	654.	751.	48617.	406.	49023.	10.9	.295	2946.
45.0	2.0	6.4	.917	60.	114.	151.	67.	63.	654.	758.	654.	751.	47967.	478.	48445.	10.7	.295	2896.

tank model with jacket.OUT

46.0	2.0	6.4	904	60.	147.	163.	67.	63.	656.	760.	654.	751.	47328.	548.	47875.	10.6	.295	2852.
47.0	2.0	6.4	892	60.	179.	175.	67.	63.	657.	761.	654.	751.	46698.	617.	47314.	10.4	.295	2814.
48.0	2.0	6.3	880	60.	210.	187.	67.	63.	659.	762.	654.	751.	46076.	685.	46761.	10.3	.295	2778.
49.0	2.0	6.3	869	60.	240.	198.	67.	63.	661.	763.	654.	751.	45461.	752.	46214.	10.2	.295	2747.
50.0	2.0	6.2	857	60.	269.	209.	67.	63.	664.	764.	654.	751.	44853.	819.	45672.	10.1	.295	2723.
51.0	2.0	6.1	846	60.	297.	220.	67.	63.	666.	765.	654.	751.	44250.	885.	45135.	10.0	.295	2700.
52.0	2.0	5.9	834	60.	323.	230.	67.	63.	669.	766.	654.	751.	43652.	951.	44603.	9.9	.295	2679.
53.0	2.0	5.8	823	60.	348.	240.	67.	63.	672.	767.	654.	751.	43058.	1016.	44074.	9.9	.295	2664.
54.0	2.0	5.6	811	60.	371.	250.	67.	63.	676.	768.	654.	751.	42467.	1081.	43548.	9.8	.295	2650.
55.0	2.0	5.4	800	60.	392.	259.	67.	63.	679.	769.	654.	751.	41879.	1145.	43024.	9.8	.295	2638.
56.0	2.0	5.2	789	60.	412.	268.	67.	63.	682.	769.	654.	751.	41293.	1209.	42502.	9.7	.295	2627.
critical wall temperature reached																		
57.0	2.0	5.1	778	60.	430.	276.	67.	63.	686.	770.	654.	751.	40709.	1273.	41983.	9.7	.295	2621.
58.0	2.0	4.9	767	60.	447.	285.	67.	63.	689.	771.	654.	751.	40127.	1337.	41464.	9.7	.295	2616.
59.0	2.0	4.7	756	60.	462.	293.	67.	63.	692.	772.	654.	751.	39546.	1401.	40947.	9.7	.295	2611.
60.0	2.0	4.5	745	60.	475.	301.	67.	63.	695.	772.	654.	751.	38966.	1465.	40430.	9.7	.295	2606.
61.0	2.0	4.3	733	60.	487.	308.	67.	63.	698.	773.	654.	751.	38387.	1528.	39915.	9.6	.295	2601.
62.0	2.0	4.2	722	60.	498.	315.	67.	63.	700.	774.	654.	751.	37809.	1591.	39400.	9.6	.295	2597.
63.0	2.0	4.1	711	60.	507.	323.	67.	63.	703.	774.	654.	751.	37231.	1655.	38886.	9.6	.295	2594.
64.0	2.0	4.0	700	60.	515.	329.	67.	63.	705.	775.	654.	751.	36655.	1718.	38373.	9.6	.295	2590.
65.0	2.0	3.9	689	60.	523.	336.	67.	63.	707.	776.	654.	751.	36079.	1781.	37860.	9.6	.295	2587.
66.0	2.0	3.8	678	60.	529.	342.	67.	63.	709.	776.	654.	751.	35504.	1844.	37349.	9.6	.295	2582.
67.0	2.0	3.7	667	60.	535.	349.	67.	63.	710.	777.	654.	751.	34931.	1907.	36838.	9.6	.295	2578.
68.0	2.0	3.6	656	60.	540.	355.	67.	63.	712.	777.	654.	751.	34358.	1970.	36328.	9.5	.295	2571.
69.0	2.0	3.6	646	60.	545.	360.	67.	63.	713.	778.	654.	751.	33786.	2032.	35819.	9.5	.295	2567.
70.0	2.0	3.5	635	60.	549.	366.	67.	63.	714.	778.	654.	751.	33216.	2095.	35311.	9.5	.295	2562.
71.0	2.0	3.5	624	60.	552.	371.	67.	63.	715.	779.	654.	751.	32646.	2157.	34804.	9.5	.295	2556.
72.0	2.0	3.4	613	60.	555.	376.	67.	63.	716.	779.	654.	751.	32079.	2220.	34298.	9.5	.295	2550.
73.0	2.0	3.4	602	60.	558.	381.	67.	63.	717.	780.	654.	751.	31512.	2282.	33794.	9.4	.295	2543.
74.0	2.0	3.3	591	60.	561.	386.	67.	63.	718.	780.	654.	751.	30948.	2344.	33291.	9.4	.295	2535.
75.0	2.0	3.3	581	60.	563.	391.	67.	63.	719.	780.	654.	751.	30384.	2405.	32790.	9.4	.295	2528.
76.0	2.0	3.3	570	60.	565.	395.	67.	63.	719.	781.	654.	751.	29823.	2467.	32290.	9.3	.295	2519.
77.0	2.0	3.3	559	60.	567.	400.	67.	63.	720.	781.	654.	751.	29264.	2528.	31792.	9.3	.295	2510.
78.0	2.0	3.2	548	60.	569.	404.	67.	63.	720.	782.	654.	751.	28706.	2589.	31296.	9.3	.295	2501.
79.0	2.0	3.2	538	60.	571.	408.	67.	63.	721.	782.	654.	751.	28151.	2650.	30801.	9.2	.295	2493.
AFTTAC model with fos = 1.600000																		
79.5	2.0	3.2	532	60.	572.	410.	67.	63.	721.	782.	654.	751.	27855.	2683.	30801.	9.2	.295	2488.
80.0	2.0	3.2	527	60.	572.	412.	67.	63.	721.	782.	654.	751.	27597.	2711.	30308.	9.2	.295	2483.
81.0	2.0	3.2	517	60.	574.	415.	67.	63.	722.	783.	654.	751.	27046.	2771.	29818.	9.2	.295	2473.

82.0	2.0	3.2	506	60.	575.	419.	67.	63.	722.	783.	654.	751.	26497.	2832.	29329.	9.1	.295	2461.
83.0	2.0	3.1	496	60.	576.	422.	67.	63.	723.	783.	654.	751.	25951.	2892.	28843.	9.1	.295	2452.
84.0	2.0	3.1	485	60.	578.	426.	67.	63.	723.	784.	654.	751.	25407.	2951.	28358.	9.0	.295	2440.
85.0	2.0	3.1	475	60.	579.	429.	67.	63.	723.	784.	654.	751.	24866.	3011.	27876.	9.0	.295	2428.
86.0	2.0	3.1	465	60.	580.	432.	67.	63.	724.	784.	654.	751.	24327.	3070.	27396.	9.0	.295	2417.
87.0	2.0	3.1	455	60.	581.	435.	67.	63.	724.	784.	654.	751.	23791.	3128.	26919.	8.9	.295	2404.
88.0	2.0	3.1	444	60.	582.	438.	67.	63.	724.	785.	654.	751.	23257.	3187.	26444.	8.9	.295	2391.
89.0	2.0	3.0	434	60.	584.	441.	67.	63.	725.	785.	654.	751.	22727.	3245.	25972.	8.8	.295	2379.
90.0	2.0	3.0	424	60.	585.	444.	67.	63.	725.	785.	654.	751.	22199.	3303.	25502.	8.8	.295	2365.
91.0	2.0	3.0	414	60.	586.	447.	67.	63.	725.	785.	654.	751.	21674.	3360.	25035.	8.7	.295	2352.
92.0	2.0	3.0	404	60.	587.	450.	67.	63.	726.	786.	654.	751.	21153.	3418.	24570.	8.7	.295	2338.
93.0	2.0	3.0	394	60.	588.	452.	67.	63.	726.	786.	654.	751.	20634.	3475.	24109.	8.6	.295	2323.
94.0	2.0	3.0	384	60.	589.	455.	67.	63.	726.	786.	654.	751.	20119.	3531.	23650.	8.6	.295	2310.
95.0	2.0	3.0	375	60.	590.	458.	67.	63.	727.	786.	654.	751.	19607.	3587.	23194.	8.5	.295	2294.
96.0	2.0	2.9	365	60.	591.	460.	67.	63.	727.	787.	654.	751.	19098.	3643.	22741.	8.5	.295	2279.
97.0	2.0	2.9	355	60.	592.	463.	67.	63.	727.	787.	654.	751.	18593.	3698.	22291.	8.4	.295	2264.
98.0	2.0	2.9	346	60.	593.	465.	67.	63.	728.	787.	654.	751.	18091.	3753.	21845.	8.3	.295	2248.
99.0	2.0	2.9	336	60.	594.	468.	67.	63.	728.	787.	654.	751.	17593.	3808.	21401.	8.3	.295	2231.
100.0	2.0	2.9	327	60.	595.	470.	67.	63.	728.	787.	654.	751.	17099.	3862.	20961.	8.2	.295	2215.
101.0	2.0	2.9	317	60.	596.	472.	67.	63.	729.	788.	654.	751.	16608.	3916.	20524.	8.1	.295	2198.
102.0	2.0	2.9	308	60.	597.	475.	67.	63.	729.	788.	654.	751.	16121.	3969.	20090.	8.1	.295	2181.
103.0	2.0	2.8	299	60.	599.	477.	67.	63.	729.	788.	654.	751.	15637.	4022.	19660.	8.0	.295	2163.
104.0	2.0	2.8	290	60.	600.	479.	67.	63.	730.	788.	654.	751.	15158.	4075.	19233.	8.0	.295	2145.
105.0	2.0	2.8	280	60.	601.	482.	67.	63.	730.	788.	654.	751.	14683.	4127.	18810.	7.9	.295	2126.
106.0	2.0	2.8	271	60.	602.	484.	67.	63.	730.	789.	654.	751.	14212.	4179.	18391.	7.8	.295	2108.
107.0	2.0	2.8	263	60.	603.	486.	67.	63.	731.	789.	654.	751.	13745.	4230.	17975.	7.7	.295	2089.
108.0	2.0	2.8	254	60.	604.	489.	67.	63.	731.	789.	654.	751.	13283.	4281.	17563.	7.7	.295	2069.
109.0	2.0	2.7	245	60.	605.	491.	67.	63.	731.	789.	654.	751.	12824.	4331.	17155.	7.6	.295	2050.
110.0	2.0	2.7	236	60.	606.	493.	67.	63.	732.	789.	654.	751.	12371.	4381.	16751.	7.5	.295	2029.
111.0	2.0	2.7	228	60.	608.	496.	67.	63.	732.	790.	654.	751.	11921.	4430.	16351.	7.4	.295	2008.
112.0	2.0	2.7	219	60.	609.	498.	67.	63.	733.	790.	654.	751.	11477.	4479.	15955.	7.4	.295	1987.
113.0	2.0	2.7	211	60.	610.	500.	67.	63.	733.	790.	654.	751.	11037.	4527.	15564.	7.3	.295	1966.
114.0	2.0	2.7	202	60.	611.	503.	67.	63.	733.	790.	654.	751.	10602.	4574.	15177.	7.2	.295	1944.
115.0	2.0	2.6	194	60.	612.	505.	67.	63.	734.	790.	654.	751.	10172.	4622.	14794.	7.1	.295	1921.
116.0	2.0	2.6	186	60.	614.	508.	67.	63.	734.	791.	654.	751.	9747.	4668.	14416.	7.0	.295	1898.
117.0	2.0	2.6	178	60.	615.	510.	67.	63.	735.	791.	654.	751.	9328.	4714.	14042.	6.9	.295	1874.
118.0	2.0	2.6	170	60.	616.	512.	67.	63.	735.	791.	654.	751.	8914.	4760.	13673.	6.9	.295	1850.
119.0	2.0	2.6	162	60.	618.	515.	67.	63.	735.	791.	654.	751.	8505.	4804.	13309.	6.8	.295	1824.
120.0	2.0	2.6	155	60.	619.	517.	67.	63.	736.	791.	654.	751.	8102.	4849.	12951.	6.7	.295	1799.



tank model with jacket.OUT

121.0	2.0	2.0	2.5	.147	60.	620.	520.	67.	63.	736.	792.	654.	751.	7705.	4892.	12597.	6.6	.295	1773.
122.0	2.0	2.0	2.5	.140	60.	622.	522.	67.	63.	737.	792.	654.	751.	7313.	4935.	12248.	6.5	.295	1746.
123.0	2.0	2.0	2.5	.132	60.	623.	525.	67.	63.	737.	792.	654.	751.	6928.	4977.	11906.	6.4	.295	1717.
124.0	2.0	2.0	2.5	.125	60.	625.	528.	67.	63.	738.	792.	654.	751.	6549.	5019.	11568.	6.3	.295	1688.
125.0	2.0	2.0	2.5	.118	60.	626.	530.	63.	63.	738.	793.	654.	751.	6177.	5060.	11237.	6.2	.295	1662.
126.0	2.0	2.0	2.4	.111	60.	628.	533.	63.	63.	739.	793.	653.	751.	5810.	5100.	10910.	6.1	.295	1639.
127.0	2.0	2.0	2.4	.104	60.	629.	536.	63.	63.	739.	793.	653.	751.	5448.	5140.	10587.	6.0	.295	1615.
128.0	2.0	2.0	2.4	.097	60.	631.	538.	63.	63.	740.	793.	653.	751.	5091.	5179.	10270.	5.9	.295	1590.
129.0	2.0	2.0	2.4	.090	60.	632.	541.	63.	63.	740.	793.	653.	751.	4740.	5217.	9958.	5.8	.295	1563.
130.0	2.0	2.0	2.4	.084	60.	634.	544.	63.	63.	741.	794.	653.	751.	4396.	5255.	9651.	5.7	.295	1535.
131.0	2.0	2.0	2.3	.077	60.	635.	547.	63.	63.	741.	794.	653.	751.	4057.	5292.	9350.	5.6	.295	1506.
132.0	2.0	2.0	2.3	.071	60.	637.	549.	63.	63.	742.	794.	653.	751.	3726.	5328.	9054.	5.5	.295	1474.
133.0	2.0	2.0	2.3	.065	60.	639.	552.	63.	63.	742.	794.	653.	751.	3402.	5364.	8766.	5.3	.295	1441.
134.0	2.0	2.0	2.3	.059	60.	640.	555.	63.	63.	743.	795.	653.	751.	3085.	5399.	8484.	5.2	.295	1406.
135.0	2.0	2.0	2.3	.053	60.	642.	558.	63.	63.	744.	795.	653.	751.	2776.	5433.	8209.	5.1	.295	1369.
136.0	2.0	2.0	2.2	.047	60.	644.	561.	63.	63.	744.	795.	653.	751.	2476.	5465.	7942.	4.9	.295	1329.
137.0	2.0	2.0	2.2	.042	60.	646.	564.	63.	63.	745.	795.	653.	751.	2185.	5497.	7683.	4.8	.295	1285.
138.0	2.0	2.0	2.2	.036	60.	647.	568.	63.	63.	746.	796.	653.	751.	1904.	5528.	7433.	4.6	.295	1239.
139.0	2.0	2.0	2.1	.031	60.	649.	571.	63.	63.	746.	796.	653.	751.	1634.	5558.	7192.	4.4	.295	1188.
140.0	2.0	2.0	2.1	.026	60.	652.	575.	63.	63.	747.	796.	653.	751.	1376.	5586.	6962.	4.2	.295	1133.
141.0	2.0	2.0	2.1	.022	60.	654.	578.	63.	63.	748.	796.	653.	751.	1130.	5613.	6743.	4.0	.295	1072.
141.4	2.0	2.0	2.1	.020	60.	655.	580.	63.	63.	748.	797.	653.	751.	1048.	5622.	6743.	3.9	.295	1050.

# Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D              =      5.770000
tank volume (m^3)      =      122.357100
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      60.000000
angle to defect bot (deg) =      150.000000
constant insulation conductance (W/m^2 K) =      22.700000
    
```

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twld C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.900	16.	17.	20.	17.	17.	394.	389.	394.	389.	55703.	197.	55900.	.0	.295	869.
2.0	.7	6.4	.902	17.	21.	31.	21.	19.	591.	619.	591.	618.	55699.	197.	55896.	.0	.295	2038.
3.0	.7	6.4	.904	18.	24.	46.	24.	21.	641.	712.	641.	710.	55695.	197.	55892.	.0	.295	2609.
4.0	.7	6.4	.907	19.	25.	60.	25.	22.	651.	741.	651.	738.	55693.	197.	55890.	.0	.295	2766.
5.0	.7	6.4	.910	20.	26.	75.	26.	23.	652.	749.	652.	745.	55688.	196.	55884.	.0	.295	2809.
6.0	.8	6.4	.913	21.	28.	90.	28.	24.	653.	752.	653.	747.	55677.	195.	55872.	.0	.295	2827.



tank model with jacket.OUT

7.0	.8	6.4	.916	22.	29.	104.	29.	25.	653.	754.	653.	747.	55672.	194.	55866.	.0	.295	2839.
8.0	.8	6.4	.919	23.	30.	118.	30.	26.	653.	755.	653.	748.	55668.	192.	55860.	.0	.295	2846.
9.0	.8	6.4	.922	24.	31.	131.	31.	27.	653.	757.	653.	748.	55665.	190.	55855.	.0	.295	2860.
10.0	.9	6.4	.926	25.	32.	144.	32.	29.	653.	758.	653.	748.	55660.	187.	55848.	.0	.295	2872.
11.0	.9	6.4	.929	27.	33.	157.	33.	30.	653.	759.	653.	748.	55654.	184.	55838.	.0	.295	2884.
12.0	.9	6.4	.932	28.	34.	169.	34.	31.	653.	760.	653.	748.	55645.	180.	55825.	.0	.295	2899.
13.0	1.0	6.4	.936	29.	35.	181.	35.	32.	653.	761.	653.	748.	55637.	176.	55813.	.0	.295	2911.
14.0	1.0	6.4	.939	30.	37.	192.	37.	33.	653.	762.	653.	748.	55631.	171.	55802.	.0	.295	2928.
15.0	1.0	6.4	.943	31.	38.	203.	38.	34.	653.	763.	653.	748.	55627.	166.	55793.	.0	.295	2937.
16.0	1.0	6.4	.947	32.	39.	213.	39.	35.	653.	764.	653.	748.	55646.	159.	55804.	.0	.295	2947.
17.0	1.1	6.4	.951	34.	40.	223.	40.	37.	653.	765.	653.	749.	55669.	151.	55819.	.0	.295	2964.
18.0	1.1	6.4	.956	35.	41.	233.	41.	38.	653.	766.	653.	749.	55691.	140.	55831.	.0	.295	2987.
19.0	1.1	6.4	.960	36.	42.	242.	43.	39.	653.	767.	653.	749.	55710.	130.	55840.	.0	.295	3006.
20.0	1.2	6.4	.965	37.	44.	251.	44.	40.	653.	768.	653.	749.	55726.	119.	55844.	.0	.295	3024.
21.0	1.2	6.4	.969	38.	45.	260.	45.	41.	653.	769.	653.	749.	55744.	106.	55850.	.0	.295	3047.
22.0	1.3	6.4	.974	40.	46.	268.	46.	42.	653.	769.	653.	749.	55758.	93.	55851.	.0	.295	3064.
23.0	1.3	6.4	.978	41.	47.	275.	47.	44.	653.	770.	653.	749.	55767.	80.	55847.	.0	.295	3089.
24.0	1.3	6.4	.983	42.	48.	283.	49.	45.	653.	771.	653.	749.	55778.	64.	55842.	.0	.295	3112.
25.0	1.4	6.4	.988	43.	50.	290.	50.	46.	653.	771.	653.	750.	55782.	48.	55830.	.0	.295	3145.
26.0	1.4	6.4	.992	44.	51.	296.	51.	47.	653.	772.	653.	750.	55781.	31.	55811.	.0	.295	3183.
27.0	1.4	6.4	.997	46.	52.	302.	52.	48.	653.	773.	653.	750.	55785.	11.	55796.	.0	.295	3255.
28.0	1.5	6.41.000	47.	53.	32.	32.	53.	50.	653.	759.	653.	750.	55647.	0.	55647.	4.7	.295	3339.
29.0	1.5	6.41.000	48.	55.	51.	51.	55.	51.	653.	752.	653.	750.	55364.	0.	55364.	4.7	.295	3335.
30.0	1.6	6.41.000	49.	56.	52.	52.	56.	52.	653.	751.	653.	750.	55057.	0.	55057.	5.2	.295	3333.
31.0	1.6	6.41.000	51.	57.	53.	53.	57.	53.	653.	750.	653.	750.	54749.	0.	54749.	5.1	.295	3329.
32.0	1.7	6.41.000	52.	58.	55.	55.	58.	55.	653.	750.	653.	750.	54444.	0.	54444.	5.1	.295	3326.
33.0	1.7	6.41.000	53.	60.	56.	56.	60.	56.	653.	750.	653.	750.	54130.	0.	54130.	5.3	.295	3322.
34.0	1.8	6.41.000	54.	61.	57.	57.	61.	57.	653.	751.	653.	751.	53816.	0.	53816.	5.2	.295	3318.
35.0	1.8	6.41.000	56.	62.	58.	58.	62.	58.	653.	751.	653.	751.	53504.	0.	53504.	5.2	.295	3313.
36.0	1.9	6.41.000	57.	63.	60.	60.	63.	60.	653.	751.	653.	751.	53173.	0.	53173.	5.6	.295	3309.
37.0	1.9	6.41.000	58.	65.	61.	61.	65.	61.	653.	751.	653.	751.	52839.	0.	52839.	5.6	.295	3305.
38.0	2.0	6.41.000	59.	66.	62.	62.	66.	62.	654.	751.	654.	751.	52506.	0.	52506.	5.5	.295	3300.
39.0	2.0	6.4	.993	60.	67.	68.	67.	63.	654.	751.	654.	751.	51979.	38.	52017.	12.1	.295	3265.
40.0	2.0	6.4	.980	60.	67.	83.	67.	63.	654.	752.	654.	751.	51265.	116.	51381.	11.7	.295	3156.
41.0	2.0	6.4	.966	60.	67.	98.	67.	63.	654.	753.	654.	751.	50572.	192.	50764.	11.4	.295	3087.
42.0	2.0	6.4	.953	60.	67.	112.	67.	63.	654.	755.	654.	751.	49892.	267.	50158.	11.2	.295	3033.
43.0	2.0	6.4	.941	60.	67.	126.	67.	63.	654.	756.	654.	751.	49222.	340.	49562.	11.1	.295	2990.
44.0	2.0	6.4	.928	60.	67.	139.	67.	63.	654.	757.	654.	751.	48561.	412.	48974.	11.0	.295	2955.
45.0	2.0	6.4	.915	60.	67.	152.	67.	63.	654.	759.	654.	751.	47908.	484.	48392.	10.8	.295	2923.

46.0	2.0	6.4	903	60.	67.	164.	67.	63.	654.	760.	654.	751.	47261.	555.	47816.	10.7	.295	2895.
47.0	2.0	6.4	891	60.	67.	176.	67.	63.	654.	761.	654.	751.	46619.	625.	47244.	10.7	.295	2873.
48.0	2.0	6.4	879	60.	67.	188.	67.	63.	654.	762.	654.	751.	45982.	695.	46677.	10.6	.295	2852.
49.0	2.0	6.4	867	60.	67.	199.	67.	63.	654.	763.	654.	751.	45349.	765.	46114.	10.5	.295	2837.
50.0	2.0	6.4	854	60.	67.	210.	67.	63.	654.	764.	654.	751.	44720.	834.	45554.	10.5	.295	2820.
51.0	2.0	6.4	843	60.	67.	221.	67.	63.	654.	765.	654.	751.	44095.	902.	44997.	10.4	.295	2806.
52.0	2.0	6.4	831	60.	67.	231.	67.	63.	654.	766.	654.	751.	43472.	970.	44442.	10.4	.295	2793.
53.0	2.0	6.4	819	60.	67.	241.	67.	63.	654.	767.	654.	751.	42852.	1038.	43891.	10.3	.295	2780.
54.0	2.0	6.4	807	60.	67.	250.	67.	63.	654.	768.	654.	751.	42235.	1106.	43341.	10.3	.295	2770.
55.0	2.0	6.4	795	60.	93.	259.	67.	63.	654.	769.	654.	751.	41620.	1174.	42794.	10.2	.295	2752.
56.0	2.0	6.4	784	60.	127.	267.	67.	63.	655.	769.	654.	751.	41010.	1240.	42251.	10.1	.295	2730.
57.0	2.0	6.4	772	60.	161.	276.	67.	63.	656.	770.	654.	751.	40405.	1307.	41712.	10.1	.295	2713.
58.0	2.0	6.3	761	60.	193.	284.	67.	63.	658.	771.	654.	751.	39803.	1373.	41176.	10.0	.295	2692.
59.0	2.0	6.3	749	60.	225.	291.	67.	63.	660.	772.	654.	751.	39206.	1438.	40644.	9.9	.295	2676.
60.0	2.0	6.2	738	60.	256.	298.	67.	63.	662.	772.	654.	751.	38612.	1503.	40116.	9.9	.295	2661.
61.0	2.0	6.1	726	60.	285.	305.	67.	63.	665.	773.	654.	751.	38022.	1568.	39590.	9.8	.295	2647.
62.0	2.0	6.0	715	60.	313.	312.	67.	63.	668.	773.	654.	751.	37434.	1633.	39066.	9.8	.295	2636.
63.0	2.0	5.8	704	60.	340.	318.	67.	63.	671.	774.	654.	751.	36849.	1697.	38546.	9.7	.295	2625.
64.0	2.0	5.6	693	60.	364.	325.	67.	63.	674.	775.	654.	751.	36266.	1761.	38027.	9.7	.295	2613.
65.0	2.0	5.4	682	60.	387.	330.	67.	63.	678.	775.	654.	751.	35686.	1824.	37510.	9.7	.295	2606.
66.0	2.0	5.2	671	60.	409.	336.	67.	63.	682.	776.	654.	751.	35107.	1888.	36995.	9.6	.295	2596.
critical wall temperature reached																		
67.0	2.0	5.1	660	60.	428.	342.	67.	63.	685.	776.	654.	751.	34530.	1951.	36481.	9.6	.295	2590.
68.0	2.0	4.9	649	60.	446.	347.	67.	63.	689.	777.	654.	751.	33955.	2014.	35969.	9.6	.295	2584.
69.0	2.0	4.7	638	60.	462.	352.	67.	63.	692.	777.	654.	751.	33381.	2077.	35458.	9.6	.295	2578.
70.0	2.0	4.5	627	60.	477.	357.	67.	63.	695.	777.	654.	751.	32808.	2140.	34948.	9.5	.295	2570.
71.0	2.0	4.3	616	60.	490.	362.	67.	63.	698.	778.	654.	751.	32237.	2202.	34439.	9.5	.295	2565.
72.0	2.0	4.2	605	60.	501.	366.	67.	63.	701.	778.	654.	751.	31667.	2265.	33932.	9.5	.295	2559.
73.0	2.0	4.0	594	60.	511.	371.	67.	63.	704.	779.	654.	751.	31098.	2327.	33425.	9.5	.295	2554.
74.0	2.0	3.9	583	60.	520.	375.	67.	63.	706.	779.	654.	751.	30530.	2390.	32920.	9.4	.295	2548.
75.0	2.0	3.8	573	60.	528.	379.	67.	63.	708.	780.	654.	751.	29964.	2452.	32416.	9.4	.295	2541.
76.0	2.0	3.7	562	60.	535.	384.	67.	63.	710.	780.	654.	751.	29400.	2514.	31913.	9.4	.295	2534.
77.0	2.0	3.6	551	60.	541.	388.	67.	63.	712.	780.	654.	751.	28836.	2575.	31412.	9.4	.295	2528.
78.0	2.0	3.5	540	60.	547.	392.	67.	63.	714.	781.	654.	751.	28275.	2637.	30912.	9.3	.295	2521.
79.0	2.0	3.5	530	60.	552.	395.	67.	63.	715.	781.	654.	751.	27715.	2698.	30413.	9.3	.295	2513.
80.0	2.0	3.4	519	60.	556.	399.	67.	63.	716.	781.	654.	751.	27157.	2759.	29916.	9.3	.295	2505.
81.0	2.0	3.4	508	60.	559.	403.	67.	63.	717.	782.	654.	751.	26601.	2820.	29421.	9.3	.295	2495.
82.0	2.0	3.3	498	60.	563.	406.	67.	63.	718.	782.	654.	751.	26047.	2881.	28928.	9.2	.295	2487.
83.0	2.0	3.3	487	60.	566.	410.	67.	63.	719.	782.	654.	751.	25495.	2942.	28436.	9.2	.295	2477.

tank model with jacket.OUT

84.0	2.0	3.2	.477	60.	568.	413.	67.	63.	720.	782.	654.	751.	24945.	3002.	27947.	9.1	.295	2467.
85.0	2.0	3.2	.466	60.	571.	416.	67.	63.	721.	783.	654.	751.	24397.	3062.	27459.	9.1	.295	2456.
AFFTAC model with fos = 1.600000																		
85.4	2.0	3.2	.462	60.	572.	418.	67.	63.	721.	783.	654.	751.	24179.	3086.	27459.	9.1	.295	2451.
86.0	2.0	3.2	.456	60.	573.	419.	67.	63.	721.	783.	654.	751.	23852.	3122.	26974.	9.1	.295	2445.
87.0	2.0	3.2	.445	60.	575.	423.	67.	63.	722.	783.	654.	751.	23309.	3181.	26491.	9.0	.295	2434.
88.0	2.0	3.1	.435	60.	577.	426.	67.	63.	723.	784.	654.	751.	22769.	3241.	26010.	9.0	.295	2422.
89.0	2.0	3.1	.425	60.	578.	429.	67.	63.	723.	784.	654.	751.	22232.	3299.	25531.	8.9	.295	2410.
90.0	2.0	3.1	.415	60.	580.	432.	67.	63.	724.	784.	654.	751.	21697.	3358.	25055.	8.9	.295	2397.
91.0	2.0	3.1	.404	60.	581.	434.	67.	63.	724.	784.	654.	751.	21166.	3416.	24582.	8.8	.295	2384.
92.0	2.0	3.0	.394	60.	583.	437.	67.	63.	724.	785.	654.	751.	20637.	3474.	24111.	8.8	.295	2371.
93.0	2.0	3.0	.384	60.	584.	440.	67.	63.	725.	785.	654.	751.	20111.	3532.	23643.	8.7	.295	2357.
94.0	2.0	3.0	.374	60.	585.	443.	67.	63.	725.	785.	654.	751.	19588.	3589.	23178.	8.7	.295	2343.
95.0	2.0	3.0	.364	60.	587.	445.	67.	63.	726.	785.	654.	751.	19069.	3646.	22715.	8.6	.295	2328.
96.0	2.0	3.0	.354	60.	588.	448.	67.	63.	726.	786.	654.	751.	18553.	3703.	22255.	8.6	.295	2313.
97.0	2.0	3.0	.345	60.	589.	451.	67.	63.	726.	786.	654.	751.	18040.	3759.	21799.	8.5	.295	2298.
98.0	2.0	2.9	.335	60.	590.	453.	67.	63.	727.	786.	654.	751.	17530.	3815.	21345.	8.5	.295	2282.
99.0	2.0	2.9	.325	60.	591.	456.	67.	63.	727.	786.	654.	751.	17024.	3870.	20895.	8.4	.295	2267.
100.0	2.0	2.9	.316	60.	593.	458.	67.	63.	727.	786.	654.	751.	16522.	3926.	20447.	8.3	.295	2250.
101.0	2.0	2.9	.306	60.	594.	461.	67.	63.	728.	787.	654.	751.	16023.	3980.	20003.	8.3	.295	2233.
102.0	2.0	2.9	.297	60.	595.	463.	67.	63.	728.	787.	654.	751.	15528.	4034.	19563.	8.2	.295	2216.
103.0	2.0	2.9	.287	60.	596.	465.	67.	63.	729.	787.	654.	751.	15037.	4088.	19126.	8.2	.295	2199.
104.0	2.0	2.9	.278	60.	597.	468.	67.	63.	729.	787.	654.	751.	14550.	4142.	18692.	8.1	.295	2180.
105.0	2.0	2.8	.269	60.	598.	470.	67.	63.	729.	787.	654.	751.	14067.	4195.	18262.	8.0	.295	2162.
106.0	2.0	2.8	.260	60.	599.	473.	67.	63.	730.	788.	654.	751.	13588.	4247.	17836.	7.9	.295	2143.
107.0	2.0	2.8	.250	60.	600.	475.	67.	63.	730.	788.	654.	751.	13114.	4299.	17413.	7.9	.295	2124.
108.0	2.0	2.8	.241	60.	602.	478.	67.	63.	730.	788.	654.	751.	12643.	4351.	16994.	7.8	.295	2105.
109.0	2.0	2.8	.233	60.	603.	480.	67.	63.	731.	788.	654.	751.	12177.	4402.	16579.	7.7	.295	2084.
110.0	2.0	2.8	.224	60.	604.	482.	67.	63.	731.	788.	654.	751.	11716.	4453.	16169.	7.6	.295	2063.
111.0	2.0	2.7	.215	60.	605.	485.	67.	63.	731.	789.	654.	751.	11259.	4503.	15762.	7.6	.295	2042.
112.0	2.0	2.7	.206	60.	606.	487.	67.	63.	732.	789.	654.	751.	10808.	4552.	15360.	7.5	.295	2020.
113.0	2.0	2.7	.198	60.	608.	490.	67.	63.	732.	789.	654.	751.	10361.	4601.	14962.	7.4	.295	1998.
114.0	2.0	2.7	.189	60.	609.	492.	67.	63.	733.	789.	654.	751.	9919.	4650.	14568.	7.3	.295	1976.
115.0	2.0	2.7	.181	60.	610.	495.	67.	63.	733.	790.	654.	751.	9482.	4698.	14179.	7.2	.295	1952.
116.0	2.0	2.7	.173	60.	611.	497.	67.	63.	733.	790.	654.	751.	9050.	4745.	13795.	7.1	.295	1928.
117.0	2.0	2.6	.165	60.	613.	500.	67.	63.	734.	790.	654.	751.	8624.	4792.	13416.	7.1	.295	1903.
118.0	2.0	2.6	.157	60.	614.	502.	67.	63.	734.	790.	654.	751.	8204.	4838.	13041.	7.0	.295	1877.
119.0	2.0	2.6	.149	60.	615.	505.	67.	63.	735.	790.	654.	751.	7789.	4883.	12672.	6.9	.295	1851.
120.0	2.0	2.6	.141	60.	617.	508.	67.	63.	735.	791.	654.	751.	7380.	4928.	12308.	6.8	.295	1824.

121.0	2.0	2.6	.133	60.	618.	510.	67.	63.	736.	791.	654.	751.	6977.	4972.	11949.	6.7	.295	1795.
122.0	2.0	2.6	.126	60.	620.	513.	67.	63.	736.	791.	654.	751.	6581.	5016.	11597.	6.5	.295	1766.
123.0	2.0	2.5	.118	60.	621.	516.	67.	63.	737.	791.	654.	751.	6191.	5058.	11249.	6.4	.295	1737.
124.0	2.0	2.5	.111	60.	623.	518.	67.	63.	737.	792.	654.	751.	5808.	5100.	10908.	6.3	.295	1706.
125.0	2.0	2.5	.104	60.	624.	521.	67.	63.	738.	792.	654.	751.	5432.	5142.	10574.	6.2	.295	1675.
126.0	2.0	2.5	.097	60.	626.	524.	67.	63.	738.	792.	654.	751.	5063.	5182.	10245.	6.1	.295	1641.
127.0	2.0	2.4	.090	60.	627.	527.	67.	63.	739.	792.	654.	751.	4702.	5222.	9924.	6.0	.295	1606.
128.0	2.0	2.4	.083	60.	629.	530.	67.	63.	739.	792.	654.	751.	4349.	5260.	9609.	5.8	.295	1570.
129.0	2.0	2.4	.076	60.	631.	533.	67.	63.	740.	793.	654.	751.	4004.	5298.	9302.	5.7	.295	1532.
130.0	2.0	2.4	.070	60.	633.	536.	67.	63.	740.	793.	654.	751.	3667.	5335.	9002.	5.5	.295	1492.
131.0	2.0	2.4	.064	60.	635.	540.	67.	63.	741.	793.	654.	751.	3340.	5371.	8711.	5.4	.295	1450.
132.0	2.0	2.3	.058	60.	636.	543.	67.	63.	742.	794.	654.	751.	3022.	5406.	8428.	5.2	.295	1407.
133.0	2.0	2.3	.052	60.	638.	546.	67.	63.	742.	794.	654.	751.	2714.	5440.	8154.	5.0	.295	1361.
134.0	2.0	2.3	.046	60.	641.	550.	67.	63.	743.	794.	654.	751.	2417.	5472.	7889.	4.9	.295	1312.
135.0	2.0	2.2	.041	60.	643.	554.	67.	63.	744.	794.	654.	751.	2130.	5504.	7634.	4.7	.295	1260.
136.0	2.0	2.2	.035	60.	645.	557.	67.	63.	745.	795.	654.	751.	1856.	5534.	7397.	4.5	.295	1204.
137.0	2.0	2.2	.030	60.	647.	561.	67.	63.	745.	795.	654.	751.	1595.	5562.	7157.	4.2	.295	1145.
138.0	2.0	2.1	.026	60.	650.	565.	63.	63.	746.	795.	653.	751.	1346.	5590.	6936.	4.0	.295	1090.
139.0	2.0	2.1	.021	60.	652.	569.	63.	63.	747.	796.	653.	751.	1110.	5616.	6725.	3.8	.295	1034.
139.3	2.0	2.1	.020	60.	653.	571.	63.	63.	747.	796.	653.	751.	1049.	5622.	6725.	3.8	.295	1018.



### Tank Model with Insulation Defects (TMID v1.0)

input data

propane		
fire temp (deg C)	=	816.000000
fire emissivity	=	1.000000
fire conv h (W/m^2K)	=	0.000000E+00
fire exposure frac	=	1.000000
tank D (m)	=	3.000000
tank L/D	=	5.770000
tank volume (m^3)	=	122.357100
tank initial fill fraction	=	9.000000E-01
wall thick (mm)	=	17.500000
PRV operating P (MPa)	=	2.000000
surface emissivity	=	9.000000E-01
lading initial temp(deg C)	=	16.000000
critical wall temp (deg C)	=	427.000000
jacket gap (mm)	=	13.000000
insul defect length (m)	=	17.310000
angle to defect top (deg)	=	90.000000
angle to defect bot (deg)	=	180.000000
constant insulation conductance (W/m^2 K) =		

time	press	pbst	fill	tlad	twvd	twvi	twli	twld	tjvd	tjvi	tjld	tjli	mliq	mvap	mtot	mdot	kins	qdottot
(min)	(MPa)	(MPa)		C	C	C	C	C	C	C	C	C	kg	kg	kg/s	W/mK	kW	
1.0	.7	6.4	.900	16.	17.	20.	17.	394.	389.	394.	389.	389.	55703.	197.	55900.	.0	.295	869.
2.0	.7	6.4	.902	17.	21.	31.	21.	591.	619.	591.	618.	55699.	197.	55896.	.0	.295	2038.	
3.0	.7	6.4	.904	18.	24.	46.	24.	641.	712.	641.	710.	55695.	197.	55892.	.0	.295	2609.	
4.0	.7	6.4	.907	19.	25.	60.	25.	651.	741.	651.	738.	55693.	197.	55890.	.0	.295	2766.	
5.0	.7	6.4	.910	20.	26.	75.	26.	652.	749.	652.	745.	55688.	196.	55884.	.0	.295	2809.	
6.0	.8	6.4	.913	21.	28.	90.	28.	653.	752.	653.	747.	55677.	195.	55872.	.0	.295	2827.	

7.0	.8	6.4	.916	22.	29.	104.	29.	25.	653.	754.	653.	747.	55672.	194.	55866.	.0	.295	2839.
8.0	.8	6.4	.919	23.	30.	118.	30.	26.	653.	755.	653.	748.	55668.	192.	55860.	.0	.295	2846.
9.0	.8	6.4	.922	24.	31.	131.	31.	27.	653.	757.	653.	748.	55665.	190.	55855.	.0	.295	2860.
10.0	.9	6.4	.926	25.	32.	144.	32.	29.	653.	758.	653.	748.	55660.	187.	55848.	.0	.295	2872.
11.0	.9	6.4	.929	27.	33.	157.	33.	30.	653.	759.	653.	748.	55654.	184.	55838.	.0	.295	2884.
12.0	.9	6.4	.932	28.	34.	169.	34.	31.	653.	760.	653.	748.	55645.	180.	55825.	.0	.295	2899.
13.0	1.0	6.4	.936	29.	35.	181.	35.	32.	653.	761.	653.	748.	55637.	176.	55813.	.0	.295	2911.
14.0	1.0	6.4	.939	30.	37.	192.	37.	33.	653.	762.	653.	748.	55631.	171.	55802.	.0	.295	2928.
15.0	1.0	6.4	.943	31.	38.	203.	38.	34.	653.	763.	653.	748.	55627.	166.	55793.	.0	.295	2937.
16.0	1.0	6.4	.947	32.	39.	213.	39.	35.	653.	764.	653.	748.	55626.	159.	55804.	.0	.295	2947.
17.0	1.1	6.4	.951	34.	40.	223.	40.	37.	653.	765.	653.	749.	55669.	151.	55819.	.0	.295	2964.
18.0	1.1	6.4	.956	35.	41.	233.	41.	38.	653.	766.	653.	749.	55691.	140.	55831.	.0	.295	2987.
19.0	1.1	6.4	.960	36.	42.	242.	42.	39.	653.	767.	653.	749.	55710.	130.	55840.	.0	.295	3006.
20.0	1.2	6.4	.965	37.	44.	251.	44.	40.	653.	768.	653.	749.	55726.	119.	55844.	.0	.295	3024.
21.0	1.2	6.4	.969	38.	45.	260.	45.	41.	653.	769.	653.	749.	55744.	106.	55850.	.0	.295	3047.
22.0	1.3	6.4	.974	40.	46.	268.	46.	42.	653.	769.	653.	749.	55758.	93.	55851.	.0	.295	3064.
23.0	1.3	6.4	.978	41.	47.	275.	47.	44.	653.	770.	653.	749.	55767.	80.	55847.	.0	.295	3089.
24.0	1.3	6.4	.983	42.	48.	283.	48.	45.	653.	771.	653.	749.	55778.	64.	55842.	.0	.295	3112.
25.0	1.4	6.4	.988	43.	50.	290.	50.	46.	653.	771.	653.	750.	55782.	48.	55830.	.0	.295	3145.
26.0	1.4	6.4	.992	44.	51.	296.	51.	47.	653.	772.	653.	750.	55781.	31.	55811.	.0	.295	3183.
27.0	1.4	6.4	.997	46.	52.	302.	52.	48.	653.	773.	653.	750.	55785.	11.	55796.	.0	.295	3255.
28.0	1.5	6.4	1.000	47.	53.	322.	53.	50.	653.	759.	653.	750.	55647.	0.	55647.	4.7	.295	3339.
29.0	1.5	6.4	1.000	48.	55.	322.	55.	51.	653.	752.	653.	750.	55364.	0.	55364.	4.7	.295	3335.
30.0	1.6	6.4	1.000	49.	56.	322.	56.	52.	653.	751.	653.	750.	55057.	0.	55057.	5.2	.295	3333.
31.0	1.6	6.4	1.000	51.	57.	322.	57.	53.	653.	750.	653.	750.	54749.	0.	54749.	5.1	.295	3329.
32.0	1.7	6.4	1.000	52.	58.	322.	58.	55.	653.	750.	653.	750.	54444.	0.	54444.	5.1	.295	3326.
33.0	1.7	6.4	1.000	53.	60.	322.	60.	56.	653.	750.	653.	750.	54130.	0.	54130.	5.3	.295	3322.
34.0	1.8	6.4	1.000	54.	61.	322.	61.	57.	653.	751.	653.	751.	53816.	0.	53816.	5.2	.295	3318.
35.0	1.8	6.4	1.000	56.	62.	322.	62.	58.	653.	751.	653.	751.	53504.	0.	53504.	5.2	.295	3313.
36.0	1.9	6.4	1.000	57.	63.	322.	63.	60.	653.	751.	653.	751.	53173.	0.	53173.	5.6	.295	3309.
37.0	1.9	6.4	1.000	58.	65.	322.	65.	61.	653.	751.	653.	751.	52839.	0.	52839.	5.6	.295	3305.
38.0	2.0	6.4	1.000	59.	66.	322.	66.	62.	654.	751.	654.	751.	52506.	0.	52506.	5.5	.295	3300.
39.0	2.0	6.4	.993	60.	67.	322.	67.	63.	654.	751.	654.	751.	51979.	38.	52017.	12.1	.295	3265.
40.0	2.0	6.4	.980	60.	67.	322.	67.	63.	654.	752.	654.	751.	51265.	116.	51381.	11.7	.295	3156.
41.0	2.0	6.4	.966	60.	67.	322.	67.	63.	654.	753.	654.	751.	50572.	192.	50764.	11.4	.295	3087.
42.0	2.0	6.4	.953	60.	67.	112.	67.	63.	654.	755.	654.	751.	49892.	267.	50158.	11.2	.295	3033.
43.0	2.0	6.4	.941	60.	67.	126.	67.	63.	654.	756.	654.	751.	49222.	340.	49562.	11.1	.295	2990.
44.0	2.0	6.4	.928	60.	67.	139.	67.	63.	654.	757.	654.	751.	48561.	412.	48974.	11.0	.295	2955.
45.0	2.0	6.4	.915	60.	67.	152.	67.	63.	654.	759.	654.	751.	47908.	484.	48392.	10.8	.295	2923.



tank model with jacket.OUT

46.0	2.0	6.4	903	60.	67.	164.	67.	63.	654.	760.	654.	751.	47261.	555.	47816.	10.7	.295	2895.
47.0	2.0	6.4	891	60.	67.	176.	67.	63.	654.	761.	654.	751.	46619.	625.	47244.	10.7	.295	2873.
48.0	2.0	6.4	879	60.	67.	188.	67.	63.	654.	762.	654.	751.	45982.	695.	46677.	10.6	.295	2852.
49.0	2.0	6.4	867	60.	67.	199.	67.	63.	654.	763.	654.	751.	45349.	765.	46114.	10.5	.295	2837.
50.0	2.0	6.4	854	60.	67.	210.	67.	63.	654.	764.	654.	751.	44720.	834.	45554.	10.5	.295	2820.
51.0	2.0	6.4	843	60.	67.	221.	67.	63.	654.	765.	654.	751.	44095.	902.	44997.	10.4	.295	2806.
52.0	2.0	6.4	831	60.	67.	231.	67.	63.	654.	766.	654.	751.	43472.	970.	44442.	10.4	.295	2793.
53.0	2.0	6.4	819	60.	67.	241.	67.	63.	654.	767.	654.	751.	42852.	1038.	43891.	10.3	.295	2780.
54.0	2.0	6.4	807	60.	67.	250.	67.	63.	654.	768.	654.	751.	42235.	1106.	43341.	10.3	.295	2770.
55.0	2.0	6.4	795	60.	67.	259.	67.	63.	654.	769.	654.	751.	41619.	1174.	42793.	10.2	.295	2761.
56.0	2.0	6.4	784	60.	67.	267.	67.	63.	654.	769.	654.	751.	41006.	1241.	42247.	10.2	.295	2752.
57.0	2.0	6.4	772	60.	67.	276.	67.	63.	654.	770.	654.	751.	40395.	1308.	41702.	10.2	.295	2746.
58.0	2.0	6.4	760	60.	67.	284.	67.	63.	654.	771.	654.	751.	39785.	1375.	41159.	10.2	.295	2738.
59.0	2.0	6.4	749	60.	67.	291.	67.	63.	654.	772.	654.	751.	39176.	1442.	40618.	10.1	.295	2732.
60.0	2.0	6.4	737	60.	67.	299.	67.	63.	654.	772.	654.	751.	38569.	1508.	40077.	10.1	.295	2727.
61.0	2.0	6.4	725	60.	67.	306.	67.	63.	654.	773.	654.	751.	37963.	1575.	39538.	10.1	.295	2721.
62.0	2.0	6.4	714	60.	67.	312.	67.	63.	654.	773.	654.	751.	37359.	1641.	38999.	10.1	.295	2716.
63.0	2.0	6.4	702	60.	67.	319.	67.	63.	654.	774.	654.	751.	36755.	1707.	38462.	10.0	.295	2711.
64.0	2.0	6.4	691	60.	67.	325.	67.	63.	654.	775.	654.	751.	36153.	1773.	37926.	10.0	.295	2705.
65.0	2.0	6.4	679	60.	67.	331.	67.	63.	654.	775.	654.	751.	35552.	1839.	37390.	10.0	.295	2701.
66.0	2.0	6.4	668	60.	67.	336.	67.	63.	654.	776.	654.	751.	34951.	1905.	36856.	10.0	.295	2696.
67.0	2.0	6.4	656	60.	67.	342.	67.	63.	654.	776.	654.	751.	34352.	1970.	36323.	10.0	.295	2690.
68.0	2.0	6.4	645	60.	67.	347.	67.	63.	654.	777.	654.	751.	33754.	2036.	35790.	10.0	.295	2687.
69.0	2.0	6.4	634	60.	67.	352.	67.	63.	654.	777.	654.	751.	33157.	2102.	35258.	9.9	.295	2682.
70.0	2.0	6.4	622	60.	67.	356.	67.	63.	654.	777.	654.	751.	32561.	2167.	34728.	9.9	.295	2676.
71.0	2.0	6.4	611	60.	67.	361.	67.	63.	654.	778.	654.	751.	31966.	2232.	34198.	9.9	.295	2672.
72.0	2.0	6.4	599	60.	67.	365.	67.	63.	654.	778.	654.	751.	31372.	2297.	33670.	9.9	.295	2667.
73.0	2.0	6.4	588	60.	67.	369.	67.	63.	654.	779.	654.	751.	30780.	2362.	33142.	9.9	.295	2660.
74.0	2.0	6.4	577	60.	67.	373.	67.	63.	654.	779.	654.	751.	30189.	2427.	32616.	9.8	.295	2655.
75.0	2.0	6.4	566	60.	67.	377.	67.	63.	654.	779.	654.	751.	29599.	2492.	32090.	9.8	.295	2650.
76.0	2.0	6.4	554	60.	67.	380.	67.	63.	654.	780.	654.	751.	29010.	2556.	31566.	9.8	.295	2644.
77.0	2.0	6.4	543	60.	67.	384.	67.	63.	654.	780.	654.	751.	28422.	2621.	31043.	9.8	.295	2637.
78.0	2.0	6.4	532	60.	67.	387.	67.	63.	654.	780.	654.	751.	27837.	2685.	30521.	9.8	.295	2631.
79.0	2.0	6.4	521	60.	67.	390.	67.	63.	654.	781.	654.	751.	27252.	2749.	30001.	9.7	.295	2624.
80.0	2.0	6.4	510	60.	67.	394.	67.	63.	654.	781.	654.	751.	26669.	2813.	29482.	9.7	.295	2617.
81.0	2.0	6.4	498	60.	71.	397.	67.	63.	654.	781.	654.	751.	26088.	2877.	28965.	9.7	.295	2609.
82.0	2.0	6.4	487	60.	110.	399.	67.	63.	654.	781.	654.	751.	25510.	2940.	28450.	9.6	.295	2591.
83.0	2.0	6.4	476	60.	147.	402.	67.	63.	656.	782.	654.	751.	24936.	3003.	27939.	9.5	.295	2573.
84.0	2.0	6.4	465	60.	184.	405.	67.	63.	657.	782.	654.	751.	24365.	3066.	27431.	9.5	.295	2554.

85.0	2.0	6.3	455	60.	220.	407.	67.	63.	659.	782.	654.	751.	23799.	3128.	26927.	9.4	.295	2536.
86.0	2.0	6.2	444	60.	255.	410.	67.	63.	662.	782.	654.	751.	23237.	3189.	26426.	9.3	.295	2518.
87.0	2.0	6.1	433	60.	288.	412.	67.	63.	665.	782.	654.	751.	22679.	3250.	25929.	9.3	.295	2500.
88.0	2.0	5.9	423	60.	320.	414.	67.	63.	668.	783.	654.	751.	22125.	3311.	25436.	9.2	.295	2484.
89.0	2.0	5.8	412	60.	350.	416.	67.	63.	672.	783.	654.	751.	21574.	3372.	24946.	9.1	.295	2467.
90.0	2.0	5.5	402	60.	378.	419.	67.	63.	676.	783.	654.	751.	21027.	3432.	24459.	9.1	.295	2451.
91.0	2.0	5.3	391	60.	404.	421.	67.	63.	680.	783.	654.	751.	20484.	3491.	23975.	9.0	.295	2435.
92.0	2.0	5.2	381	60.	427.	423.	67.	63.	685.	783.	654.	751.	19944.	3550.	23494.	9.0	.295	2419.
critical wall temperature reached																		
93.0	2.0	4.9	371	60.	449.	425.	67.	63.	689.	784.	654.	751.	19407.	3609.	23017.	8.9	.295	2404.
94.0	2.0	4.6	361	60.	468.	427.	67.	63.	693.	784.	654.	751.	18874.	3668.	22542.	8.9	.295	2389.
95.0	2.0	4.4	350	60.	486.	429.	67.	63.	697.	784.	654.	751.	18345.	3726.	22070.	8.8	.295	2375.
96.0	2.0	4.2	340	60.	501.	431.	67.	63.	701.	784.	654.	751.	17818.	3783.	21602.	8.7	.295	2359.
97.0	2.0	4.0	330	60.	515.	433.	67.	63.	704.	784.	654.	751.	17295.	3841.	21136.	8.7	.295	2344.
98.0	2.0	3.8	320	60.	527.	436.	67.	63.	708.	784.	654.	751.	16775.	3898.	20673.	8.6	.295	2328.
99.0	2.0	3.7	311	60.	538.	438.	67.	63.	710.	785.	654.	751.	16259.	3954.	20213.	8.6	.295	2314.
100.0	2.0	3.5	301	60.	547.	440.	67.	63.	713.	785.	654.	751.	15746.	4011.	19756.	8.5	.295	2298.
101.0	2.0	3.4	291	60.	555.	442.	67.	63.	715.	785.	654.	751.	15236.	4067.	19303.	8.5	.295	2283.
102.0	2.0	3.3	281	60.	562.	445.	67.	63.	718.	785.	654.	751.	14730.	4122.	18852.	8.4	.295	2266.
103.0	2.0	3.3	272	60.	568.	447.	67.	63.	719.	785.	654.	751.	14228.	4177.	18405.	8.3	.295	2249.
AFFTAC model with fos = 1.600000																		
103.8	2.0	3.2	265	60.	572.	449.	67.	63.	721.	786.	654.	751.	13854.	4218.	18405.	8.3	.295	2236.
104.0	2.0	3.2	262	60.	573.	449.	67.	63.	721.	786.	654.	751.	13730.	4232.	17961.	8.3	.295	2232.
105.0	2.0	3.1	253	60.	577.	452.	67.	63.	722.	786.	654.	751.	13235.	4286.	17521.	8.2	.295	2214.
106.0	2.0	3.1	243	60.	582.	454.	67.	63.	724.	786.	654.	751.	12745.	4340.	17084.	8.1	.295	2196.
107.0	2.0	3.0	234	60.	585.	456.	67.	63.	725.	786.	654.	751.	12258.	4393.	16651.	8.1	.295	2176.
108.0	2.0	3.0	225	60.	588.	459.	67.	63.	726.	786.	654.	751.	11776.	4446.	16222.	8.0	.295	2157.
109.0	2.0	2.9	216	60.	591.	461.	67.	63.	727.	787.	654.	751.	11299.	4498.	15797.	7.9	.295	2136.
110.0	2.0	2.9	207	60.	594.	464.	67.	63.	728.	787.	654.	751.	10826.	4550.	15376.	7.8	.295	2115.
111.0	2.0	2.9	198	60.	596.	466.	67.	63.	728.	787.	654.	751.	10358.	4601.	14959.	7.8	.295	2094.
112.0	2.0	2.8	189	60.	598.	469.	67.	63.	729.	787.	654.	751.	9894.	4652.	14547.	7.7	.295	2072.
113.0	2.0	2.8	180	60.	600.	471.	67.	63.	730.	788.	654.	751.	9436.	4703.	14139.	7.6	.295	2049.
114.0	2.0	2.8	172	60.	602.	474.	67.	63.	730.	788.	654.	751.	8983.	4752.	13735.	7.5	.295	2025.
115.0	2.0	2.8	163	60.	604.	477.	67.	63.	731.	788.	654.	751.	8535.	4801.	13336.	7.4	.295	2000.
116.0	2.0	2.7	155	60.	606.	479.	67.	63.	732.	788.	654.	751.	8093.	4850.	12943.	7.3	.295	1975.
117.0	2.0	2.7	146	60.	607.	482.	67.	63.	732.	788.	654.	751.	7656.	4898.	12554.	7.2	.295	1950.
118.0	2.0	2.7	138	60.	609.	485.	67.	63.	733.	789.	654.	751.	7226.	4945.	12170.	7.1	.295	1922.
119.0	2.0	2.7	130	60.	611.	488.	67.	63.	733.	789.	654.	751.	6801.	4991.	11793.	7.0	.295	1893.
120.0	2.0	2.7	122	60.	612.	490.	67.	63.	734.	789.	654.	751.	6383.	5037.	11420.	6.9	.295	1864.

tank model with jacket.OUT

121.0	2.0	2.6	.114	60.	614.	493.	67.	63.	734.	789.	654.	751.	5972.	5082.	11054.	6.8	.295	1834.
122.0	2.0	2.6	.106	60.	615.	496.	67.	63.	735.	790.	654.	751.	5567.	5127.	10694.	6.7	.295	1801.
123.0	2.0	2.6	.099	60.	617.	499.	67.	63.	735.	790.	654.	751.	5170.	5170.	10340.	6.6	.295	1768.
124.0	2.0	2.6	.091	60.	619.	502.	67.	63.	736.	790.	654.	751.	4780.	5213.	9993.	6.4	.295	1734.
125.0	2.0	2.5	.084	60.	620.	505.	67.	63.	736.	790.	654.	751.	4399.	5255.	9654.	6.3	.295	1697.
126.0	2.0	2.5	.077	60.	622.	509.	67.	63.	737.	791.	654.	751.	4025.	5296.	9321.	6.2	.295	1659.
127.0	2.0	2.5	.070	60.	624.	512.	67.	63.	737.	791.	654.	751.	3661.	5336.	8997.	6.0	.295	1618.
128.0	2.0	2.5	.063	60.	626.	515.	67.	63.	738.	791.	654.	751.	3305.	5375.	8680.	5.8	.295	1576.
129.0	2.0	2.4	.056	60.	627.	519.	67.	63.	739.	791.	654.	751.	2960.	5413.	8372.	5.7	.295	1530.
130.0	2.0	2.4	.050	60.	629.	522.	67.	63.	739.	792.	654.	751.	2625.	5449.	8074.	5.5	.295	1481.
131.0	2.0	2.4	.044	60.	631.	526.	67.	63.	740.	792.	654.	751.	2301.	5485.	7786.	5.3	.295	1430.
132.0	2.0	2.4	.038	60.	633.	530.	67.	63.	741.	792.	654.	751.	1989.	5519.	7508.	5.1	.295	1374.
133.0	2.0	2.3	.032	60.	636.	534.	67.	63.	741.	793.	654.	751.	1690.	5552.	7241.	4.9	.295	1313.
134.0	2.0	2.3	.027	60.	638.	538.	67.	63.	742.	793.	654.	751.	1405.	5583.	6988.	4.6	.295	1246.
135.0	2.0	2.3	.022	60.	640.	542.	67.	63.	743.	793.	654.	751.	1135.	5613.	6748.	4.3	.295	1173.
135.3	2.0	2.3	.020	60.	641.	544.	67.	63.	743.	794.	654.	751.	1049.	5622.	6748.	4.3	.295	1146.

TMID effect of fill

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      8.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K) =      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.600000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	85.7	2.0	570.0	60.0	.595	34413.9
.0	20.0	80.4	2.0	570.0	60.0	.628	35867.5
.0	30.0	74.7	2.0	570.0	60.0	.668	37933.1
.0	40.0	67.9	2.0	570.0	60.0	.723	40654.5
.0	50.0	61.3	2.0	570.0	60.0	.779	43040.5
.0	60.0	57.8	2.0	570.0	60.0	.804	44458.8
.0	70.0	56.6	2.0	570.1	60.0	.798	44153.4
.0	80.0	55.5	2.0	570.1	60.0	.793	43858.9
.0	90.0	54.3	2.0	570.0	60.0	.790	43590.0
.0	100.0	53.3	2.0	570.0	60.0	.785	43368.2
.0	110.0	52.4	2.0	570.0	60.0	.781	43184.3
.0	120.0	51.5	2.0	570.0	60.0	.775	43011.5
.0	130.0	50.7	2.0	570.0	60.0	.769	42861.5
.0	140.0	49.9	2.0	570.0	60.0	.764	42768.3
.0	150.0	49.1	2.0	570.0	60.0	.759	42040.9
.0	160.0	48.5	2.0	570.1	60.0	.752	41968.9
.0	170.0	47.8	2.0	570.0	60.0	.747	41937.6
.0	180.0	47.1	2.0	569.9	60.0	.742	41246.8



Tank Model with Insulation Defects (TMID v1.0)

input data

propane  
fire temp (deg C) = 816.000000  
fire emissivity = 1.000000  
fire conv h (W/m^2K) = 0.000000E+00  
fire exposure frac = 1.000000  
tank D (m) = 3.000000  
tank L/D = 5.770000  
tank volume (m^3) = 122.357100  
tank initial fill fraction = 8.000000E-01  
wall thick (mm) = 17.500000  
PRV operating P (MPa) = 2.000000  
surface emissivity = 9.000000E-01  
lading initial temp(deg C) = 16.000000  
critical wall temp (deg C) = 427.000000  
jacket gap (mm) = 13.000000  
insul defect length (m) = 17.310000  
angle to defect top (deg) = 0.000000E+00  
angle to defect bot (deg) = 90.000000  
constant insulation conductance (W/m^2 K)= 22.700000

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twvd C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.800	16.	19.	20.	17.	17.	394.	389.	394.	389.	49513.	395.	49908.	.0	.295	788.
2.0	.7	6.4	.801	17.	37.	31.	21.	19.	591.	619.	591.	618.	49506.	398.	49904.	.0	.295	1596.
3.0	.7	6.4	.803	17.	67.	46.	24.	20.	642.	712.	641.	710.	49497.	404.	49901.	.0	.295	1977.
4.0	.7	6.4	.805	18.	99.	61.	25.	21.	652.	741.	651.	738.	49484.	409.	49893.	.0	.295	2096.
5.0	.7	6.4	.808	19.	131.	76.	26.	22.	655.	749.	652.	745.	49488.	414.	49902.	.0	.295	2131.
6.0	.7	6.4	.810	20.	163.	90.	27.	23.	656.	752.	653.	747.	49487.	419.	49906.	.0	.295	2158.



tank model with jacket.OUT

7.0	.8	6.3	.812	21.	195.	105.	28.	24.	658.	754.	653.	747.	49481.	425.	49906.	.0	.295	2177.
8.0	.8	6.3	.814	22.	225.	119.	29.	25.	660.	755.	653.	748.	49473.	430.	49903.	.0	.295	2197.
9.0	.8	6.2	.817	23.	254.	132.	30.	26.	662.	757.	653.	748.	49461.	435.	49896.	.0	.295	2224.
10.0	.8	6.1	.819	24.	282.	146.	31.	27.	665.	758.	653.	748.	49444.	441.	49884.	.0	.295	2249.
11.0	.9	6.0	.821	25.	309.	159.	32.	28.	668.	759.	653.	748.	49430.	446.	49877.	.0	.295	2277.
12.0	.9	5.9	.823	26.	334.	172.	33.	29.	671.	760.	653.	748.	49414.	451.	49865.	.0	.295	2306.
13.0	.9	5.7	.826	27.	358.	184.	34.	30.	674.	762.	653.	748.	49401.	456.	49856.	.0	.295	2337.
14.0	.9	5.5	.829	28.	380.	196.	35.	31.	677.	763.	653.	748.	49383.	461.	49844.	.0	.295	2367.
15.0	1.0	5.3	.832	29.	401.	208.	36.	32.	680.	764.	653.	748.	49392.	465.	49856.	.0	.295	2394.
16.0	1.0	5.1	.835	30.	420.	220.	37.	33.	684.	765.	653.	748.	49399.	468.	49867.	.0	.295	2430.
critical wall temperature reached																		
17.0	1.0	5.0	.838	31.	437.	231.	38.	34.	687.	766.	653.	748.	49399.	472.	49871.	.0	.295	2465.
18.0	1.0	4.8	.841	32.	453.	242.	39.	35.	690.	767.	653.	749.	49392.	476.	49868.	.0	.295	2499.
19.0	1.0	4.6	.844	34.	467.	253.	40.	37.	693.	768.	653.	749.	49378.	480.	49859.	.0	.295	2532.
20.0	1.1	4.4	.847	35.	479.	263.	41.	38.	696.	769.	653.	749.	49360.	483.	49843.	.0	.295	2564.
21.0	1.1	4.3	.850	36.	491.	273.	42.	39.	699.	770.	653.	749.	49346.	486.	49832.	.0	.295	2591.
22.0	1.2	4.2	.853	37.	501.	282.	43.	40.	701.	771.	653.	749.	49326.	489.	49816.	.0	.295	2622.
23.0	1.2	4.0	.856	38.	509.	291.	45.	41.	704.	771.	653.	749.	49307.	491.	49799.	.0	.295	2648.
24.0	1.2	3.9	.859	39.	517.	300.	46.	42.	706.	772.	653.	749.	49295.	493.	49788.	.0	.295	2670.
25.0	1.3	3.8	.863	40.	524.	308.	47.	43.	707.	773.	653.	749.	49313.	492.	49806.	.0	.295	2688.
26.0	1.3	3.8	.868	41.	530.	316.	48.	44.	709.	774.	653.	749.	49332.	491.	49823.	.0	.295	2712.
27.0	1.4	3.7	.872	43.	535.	323.	49.	46.	710.	774.	653.	749.	49349.	488.	49836.	.0	.295	2735.
28.0	1.4	3.6	.876	44.	539.	331.	50.	47.	712.	775.	653.	750.	49360.	485.	49845.	.0	.295	2758.
29.0	1.4	3.6	.881	45.	543.	337.	52.	48.	713.	776.	653.	750.	49368.	482.	49850.	.0	.295	2778.
30.0	1.5	3.5	.885	46.	546.	343.	53.	49.	714.	776.	653.	750.	49375.	477.	49852.	.0	.295	2796.
31.0	1.5	3.5	.890	47.	549.	349.	54.	50.	715.	777.	653.	750.	49377.	472.	49849.	.0	.295	2815.
32.0	1.6	3.5	.894	49.	552.	355.	55.	52.	715.	777.	653.	750.	49379.	465.	49845.	.0	.295	2833.
33.0	1.6	3.4	.899	50.	554.	360.	56.	53.	716.	778.	653.	750.	49387.	456.	49843.	.0	.295	2850.
34.0	1.6	3.4	.904	51.	556.	365.	58.	54.	716.	778.	653.	750.	49392.	446.	49838.	.0	.295	2868.
35.0	1.7	3.4	.909	52.	557.	369.	59.	55.	717.	779.	653.	750.	49393.	435.	49828.	.0	.295	2880.
36.0	1.7	3.4	.914	53.	558.	373.	60.	56.	717.	779.	653.	750.	49396.	422.	49818.	.0	.295	2896.
37.0	1.8	3.4	.919	55.	560.	377.	61.	58.	718.	779.	653.	751.	49395.	408.	49803.	.0	.295	2911.
38.0	1.8	3.4	.924	56.	560.	380.	62.	59.	718.	780.	653.	751.	49390.	394.	49785.	.0	.295	2925.
39.0	1.9	3.3	.930	57.	561.	383.	64.	60.	718.	780.	653.	751.	49386.	376.	49762.	.0	.295	2938.
40.0	1.9	3.3	.935	58.	562.	386.	65.	61.	718.	780.	653.	751.	49379.	356.	49735.	.0	.295	2955.
41.0	2.0	3.3	.941	59.	562.	389.	66.	62.	719.	780.	654.	751.	49369.	336.	49705.	.0	.295	2968.
42.0	2.0	3.3	.937	60.	563.	391.	67.	63.	719.	781.	654.	751.	49022.	362.	49384.	11.6	.295	3119.
43.0	2.0	3.3	.923	60.	563.	394.	67.	63.	719.	781.	654.	751.	48330.	438.	48768.	11.5	.295	3098.
44.0	2.0	3.3	.910	60.	564.	396.	67.	63.	719.	781.	654.	751.	47644.	513.	48157.	11.4	.295	3067.

45.0	2.0	3.3	.897	60.	564.	398.	67.	63.	719.	781.	654.	751.	46965.	588.	47552.	11.3	.295	3038.
46.0	2.0	3.3	.885	60.	565.	401.	67.	63.	719.	781.	654.	751.	46291.	661.	46953.	11.2	.295	3014.
47.0	2.0	3.3	.872	60.	566.	403.	67.	63.	719.	782.	654.	751.	45623.	735.	46358.	11.1	.295	2989.
48.0	2.0	3.3	.859	60.	566.	405.	67.	63.	720.	782.	654.	751.	44961.	807.	45768.	11.0	.295	2966.
49.0	2.0	3.3	.847	60.	567.	408.	67.	63.	720.	782.	654.	751.	44303.	879.	45183.	10.9	.295	2943.
50.0	2.0	3.3	.834	60.	567.	410.	67.	63.	720.	782.	654.	751.	43651.	951.	44601.	10.8	.295	2923.
51.0	2.0	3.2	.822	60.	568.	412.	67.	63.	720.	782.	654.	751.	43003.	1022.	44025.	10.8	.295	2902.
52.0	2.0	3.2	.809	60.	569.	414.	67.	63.	720.	783.	654.	751.	42359.	1092.	43452.	10.7	.295	2884.
53.0	2.0	3.2	.797	60.	570.	417.	67.	63.	721.	783.	654.	751.	41720.	1163.	42883.	10.6	.295	2863.
54.0	2.0	3.2	.785	60.	570.	419.	67.	63.	721.	783.	654.	751.	41085.	1232.	42317.	10.5	.295	2844.
55.0	2.0	3.2	.773	60.	571.	421.	67.	63.	721.	783.	654.	751.	40455.	1301.	41756.	10.5	.295	2825.
56.0	2.0	3.2	.761	60.	572.	423.	67.	63.	721.	783.	654.	751.	39828.	1370.	41198.	10.4	.295	2809.
AFFTAC model with fos = 1.600000																		
56.0	2.0	3.2	.761	60.	572.	423.	67.	63.	721.	783.	654.	751.	39818.	1371.	41198.	10.4	.295	2808.
57.0	2.0	3.2	.749	60.	572.	425.	67.	63.	721.	784.	654.	751.	39206.	1438.	40644.	10.3	.295	2789.
58.0	2.0	3.2	.737	60.	573.	427.	67.	63.	722.	784.	654.	751.	38587.	1506.	40093.	10.3	.295	2773.
59.0	2.0	3.2	.726	60.	574.	429.	67.	63.	722.	784.	654.	751.	37972.	1574.	39546.	10.2	.295	2756.
60.0	2.0	3.2	.714	60.	574.	432.	67.	63.	722.	784.	654.	751.	37361.	1640.	39002.	10.2	.295	2739.
61.0	2.0	3.2	.702	60.	575.	434.	67.	63.	722.	784.	654.	751.	36754.	1707.	38461.	10.1	.295	2721.
62.0	2.0	3.1	.691	60.	576.	436.	67.	63.	722.	785.	654.	751.	36151.	1773.	37924.	10.0	.295	2704.
63.0	2.0	3.1	.679	60.	577.	438.	67.	63.	723.	785.	654.	751.	35551.	1839.	37390.	10.0	.295	2688.
64.0	2.0	3.1	.668	60.	577.	440.	67.	63.	723.	785.	654.	751.	34955.	1904.	36859.	9.9	.295	2671.
65.0	2.0	3.1	.657	60.	578.	442.	67.	63.	723.	785.	654.	751.	34363.	1969.	36332.	9.8	.295	2655.
66.0	2.0	3.1	.645	60.	579.	443.	67.	63.	723.	785.	654.	751.	33774.	2034.	35808.	9.8	.295	2638.
67.0	2.0	3.1	.634	60.	579.	445.	67.	63.	724.	785.	654.	751.	33189.	2098.	35287.	9.7	.295	2622.
68.0	2.0	3.1	.623	60.	580.	447.	67.	63.	724.	786.	654.	751.	32607.	2162.	34769.	9.7	.295	2606.
69.0	2.0	3.1	.612	60.	581.	449.	67.	63.	724.	786.	654.	751.	32030.	2225.	34255.	9.6	.295	2590.
70.0	2.0	3.1	.601	60.	582.	451.	67.	63.	724.	786.	654.	751.	31455.	2288.	33743.	9.5	.295	2573.
71.0	2.0	3.1	.590	60.	582.	453.	67.	63.	724.	786.	654.	751.	30885.	2351.	33235.	9.5	.295	2557.
72.0	2.0	3.0	.579	60.	583.	455.	67.	63.	725.	786.	654.	751.	30317.	2413.	32730.	9.4	.295	2540.
73.0	2.0	3.0	.568	60.	584.	457.	67.	63.	725.	786.	654.	751.	29754.	2475.	32228.	9.4	.295	2526.
74.0	2.0	3.0	.558	60.	585.	459.	67.	63.	725.	786.	654.	751.	29194.	2536.	31730.	9.3	.295	2510.
75.0	2.0	3.0	.547	60.	586.	460.	67.	63.	725.	787.	654.	751.	28637.	2597.	31234.	9.2	.295	2494.
76.0	2.0	3.0	.537	60.	586.	462.	67.	63.	726.	787.	654.	751.	28085.	2658.	30742.	9.2	.295	2478.
77.0	2.0	3.0	.526	60.	587.	464.	67.	63.	726.	787.	654.	751.	27535.	2718.	30253.	9.1	.295	2461.
78.0	2.0	3.0	.516	60.	588.	466.	67.	63.	726.	787.	654.	751.	26990.	2778.	29767.	9.1	.295	2445.
79.0	2.0	3.0	.505	60.	589.	468.	67.	63.	726.	787.	654.	751.	26448.	2837.	29285.	9.0	.295	2429.
80.0	2.0	3.0	.495	60.	589.	470.	63.	63.	727.	787.	653.	751.	25909.	2896.	28805.	8.9	.295	2414.
81.0	2.0	2.9	.485	60.	590.	471.	63.	63.	727.	788.	653.	751.	25373.	2955.	28328.	8.9	.295	2404.

tank model with jacket.OUT

82.0	2.0	2.0	2.9	.475	60.	591.	473.	63.	63.	727.	788.	653.	751.	24840.	3013.	27853.	8.9	.295	2392.
83.0	2.0	2.0	2.9	.464	60.	592.	475.	63.	63.	727.	788.	653.	751.	24309.	3072.	27381.	8.8	.295	2380.
84.0	2.0	2.0	2.9	.454	60.	592.	476.	63.	63.	728.	788.	653.	751.	23781.	3129.	26911.	8.8	.295	2368.
85.0	2.0	2.0	2.9	.444	60.	593.	478.	63.	63.	728.	788.	653.	751.	23256.	3187.	26443.	8.7	.295	2355.
86.0	2.0	2.0	2.9	.434	60.	594.	480.	63.	63.	728.	788.	653.	751.	22733.	3244.	25978.	8.7	.295	2344.
87.0	2.0	2.0	2.9	.424	60.	595.	481.	63.	63.	728.	788.	653.	751.	22214.	3301.	25515.	8.6	.295	2330.
88.0	2.0	2.0	2.9	.415	60.	595.	483.	63.	63.	728.	789.	653.	751.	21697.	3358.	25055.	8.6	.295	2317.
89.0	2.0	2.0	2.9	.405	60.	596.	484.	63.	63.	729.	789.	653.	751.	21183.	3414.	24597.	8.5	.295	2304.
90.0	2.0	2.0	2.9	.395	60.	597.	486.	63.	63.	729.	789.	653.	751.	20671.	3470.	24142.	8.5	.295	2291.
91.0	2.0	2.0	2.9	.385	60.	597.	487.	63.	63.	729.	789.	653.	751.	20163.	3526.	23689.	8.4	.295	2277.
92.0	2.0	2.0	2.8	.376	60.	598.	489.	63.	63.	729.	789.	653.	751.	19658.	3582.	23240.	8.4	.295	2264.
93.0	2.0	2.0	2.8	.366	60.	599.	491.	63.	63.	729.	789.	653.	751.	19156.	3637.	22793.	8.3	.295	2250.
94.0	2.0	2.0	2.8	.356	60.	599.	492.	63.	63.	730.	789.	653.	751.	18657.	3691.	22348.	8.3	.295	2236.
95.0	2.0	2.0	2.8	.347	60.	600.	494.	63.	63.	730.	789.	653.	751.	18161.	3746.	21907.	8.2	.295	2222.
96.0	2.0	2.0	2.8	.338	60.	601.	495.	63.	63.	730.	790.	653.	751.	17669.	3800.	21468.	8.2	.295	2208.
97.0	2.0	2.0	2.8	.328	60.	601.	497.	63.	63.	730.	790.	653.	751.	17179.	3853.	21033.	8.1	.295	2193.
98.0	2.0	2.0	2.8	.319	60.	602.	498.	63.	63.	730.	790.	653.	751.	16693.	3907.	20600.	8.1	.295	2177.
99.0	2.0	2.0	2.8	.310	60.	603.	500.	63.	63.	731.	790.	653.	751.	16210.	3960.	20170.	8.0	.295	2162.
100.0	2.0	2.0	2.8	.301	60.	603.	501.	63.	63.	731.	790.	653.	751.	15731.	4012.	19743.	8.0	.295	2147.
101.0	2.0	2.0	2.8	.291	60.	604.	503.	63.	63.	731.	790.	653.	751.	15255.	4064.	19320.	7.9	.295	2132.
102.0	2.0	2.0	2.8	.282	60.	605.	504.	63.	63.	731.	790.	653.	751.	14783.	4116.	18899.	7.8	.295	2115.
103.0	2.0	2.0	2.7	.273	60.	606.	506.	63.	63.	732.	791.	653.	751.	14314.	4167.	18482.	7.8	.295	2099.
104.0	2.0	2.0	2.7	.265	60.	606.	507.	63.	63.	732.	791.	653.	751.	13849.	4218.	18068.	7.7	.295	2082.
105.0	2.0	2.0	2.7	.256	60.	607.	509.	63.	63.	732.	791.	653.	751.	13388.	4269.	17657.	7.7	.295	2066.
106.0	2.0	2.0	2.7	.247	60.	608.	511.	63.	63.	732.	791.	653.	751.	12930.	4319.	17249.	7.6	.295	2048.
107.0	2.0	2.0	2.7	.238	60.	609.	512.	63.	63.	733.	791.	653.	751.	12476.	4369.	16845.	7.5	.295	2031.
108.0	2.0	2.0	2.7	.230	60.	610.	514.	63.	63.	733.	791.	653.	751.	12026.	4418.	16445.	7.5	.295	2013.
109.0	2.0	2.0	2.7	.221	60.	611.	515.	63.	63.	733.	791.	653.	751.	11581.	4467.	16048.	7.4	.295	1995.
110.0	2.0	2.0	2.7	.213	60.	611.	517.	63.	63.	733.	791.	653.	751.	11139.	4516.	15654.	7.3	.295	1977.
111.0	2.0	2.0	2.7	.204	60.	612.	519.	63.	63.	734.	792.	653.	751.	10701.	4564.	15265.	7.3	.295	1957.
112.0	2.0	2.0	2.6	.196	60.	613.	521.	63.	63.	734.	792.	653.	751.	10268.	4611.	14879.	7.2	.295	1939.
113.0	2.0	2.0	2.6	.188	60.	614.	522.	63.	63.	734.	792.	653.	751.	9839.	4658.	14497.	7.1	.295	1919.
114.0	2.0	2.0	2.6	.180	60.	615.	524.	63.	63.	735.	792.	653.	751.	9414.	4705.	14119.	7.0	.295	1898.
115.0	2.0	2.0	2.6	.172	60.	616.	526.	63.	63.	735.	792.	653.	751.	8994.	4751.	13745.	7.0	.295	1878.
116.0	2.0	2.0	2.6	.164	60.	617.	528.	63.	63.	735.	792.	653.	751.	8579.	4796.	13375.	6.9	.295	1856.
117.0	2.0	2.0	2.6	.156	60.	618.	530.	63.	63.	736.	793.	653.	751.	8169.	4841.	13010.	6.8	.295	1834.
118.0	2.0	2.0	2.6	.148	60.	619.	532.	63.	63.	736.	793.	653.	751.	7763.	4886.	12649.	6.7	.295	1812.
119.0	2.0	2.0	2.5	.141	60.	620.	533.	63.	63.	736.	793.	653.	751.	7363.	4930.	12292.	6.6	.295	1788.
120.0	2.0	2.0	2.5	.133	60.	621.	535.	63.	63.	737.	793.	653.	751.	6968.	4973.	11941.	6.5	.295	1764.

121.0	2.0	2.0	2.5	.126	60.	623.	537.	63.	63.	737.	793.	653.	751.	6578.	5016.	11594.	6.4	.295	1739.
122.0	2.0	2.0	2.5	.118	60.	624.	540.	63.	63.	738.	793.	653.	751.	6194.	5058.	11252.	6.4	.295	1713.
123.0	2.0	2.0	2.5	.111	60.	625.	542.	63.	63.	738.	794.	653.	751.	5816.	5099.	10915.	6.3	.295	1687.
124.0	2.0	2.0	2.5	.104	60.	626.	544.	63.	63.	738.	794.	653.	751.	5443.	5140.	10584.	6.2	.295	1660.
125.0	2.0	2.0	2.4	.097	60.	628.	546.	63.	63.	739.	794.	653.	751.	5077.	5180.	10258.	6.0	.295	1631.
126.0	2.0	2.0	2.4	.090	60.	629.	548.	63.	63.	739.	794.	653.	751.	4718.	5220.	9938.	5.9	.295	1600.
127.0	2.0	2.0	2.4	.083	60.	630.	551.	63.	63.	740.	794.	653.	751.	4365.	5258.	9624.	5.8	.295	1569.
128.0	2.0	2.0	2.4	.077	60.	632.	553.	63.	63.	740.	794.	653.	751.	4020.	5296.	9316.	5.7	.295	1536.
129.0	2.0	2.0	2.4	.070	60.	633.	556.	63.	63.	741.	795.	653.	751.	3682.	5333.	9015.	5.6	.295	1502.
130.0	2.0	2.0	2.3	.064	60.	635.	558.	63.	63.	741.	795.	653.	751.	3352.	5369.	8721.	5.4	.295	1466.
131.0	2.0	2.0	2.3	.058	60.	637.	561.	63.	63.	742.	795.	653.	751.	3030.	5405.	8434.	5.3	.295	1428.
132.0	2.0	2.0	2.3	.052	60.	638.	564.	63.	63.	742.	795.	653.	751.	2716.	5439.	8156.	5.1	.295	1387.
133.0	2.0	2.0	2.3	.046	60.	640.	566.	63.	63.	743.	796.	653.	751.	2413.	5472.	7885.	5.0	.295	1344.
134.0	2.0	2.0	2.3	.040	60.	642.	569.	63.	63.	744.	796.	653.	751.	2119.	5505.	7623.	4.8	.295	1297.
135.0	2.0	2.0	2.2	.035	60.	644.	572.	63.	63.	744.	796.	653.	751.	1835.	5536.	7371.	4.6	.295	1248.
136.0	2.0	2.0	2.2	.030	60.	646.	576.	63.	63.	745.	796.	653.	751.	1564.	5565.	7129.	4.4	.295	1194.
137.0	2.0	2.0	2.2	.025	60.	648.	579.	63.	63.	746.	797.	653.	751.	1304.	5594.	6898.	4.2	.295	1135.
138.0	2.0	2.0	2.1	.020	60.	651.	582.	63.	63.	747.	797.	653.	751.	1059.	5621.	6680.	4.0	.295	1069.
138.1	2.0	2.0	2.1	.020	60.	651.	583.	63.	63.	747.	797.	653.	751.	1047.	5622.	6680.	4.0	.295	1066.



# Tank Model with Insulation Defects (TMID v1.0)

## input data

```

propane
fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D               =      5.770000
tank volume (m^3)      =      122.357100
tank initial fill fraction =      5.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      0.000000E+00
angle to defect bot (deg) =      90.000000
constant insulation conductance (W/m^2 K)=

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22.700000

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twvd C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.500	16.	19.	20.	17.	18.	394.	389.	394.	389.	30942.	989.	31931.	.0	.295	587.
2.0	.7	6.4	.501	17.	37.	31.	21.	19.	591.	619.	591.	618.	30926.	1003.	31929.	.0	.295	1079.
3.0	.7	6.4	.502	18.	67.	46.	24.	20.	642.	712.	641.	710.	30904.	1023.	31927.	.0	.295	1304.
4.0	.7	6.4	.502	18.	99.	61.	25.	21.	652.	741.	651.	738.	30874.	1044.	31918.	.0	.295	1384.
5.0	.7	6.4	.503	19.	132.	76.	26.	22.	655.	749.	652.	745.	30856.	1067.	31922.	.0	.295	1408.
6.0	.7	6.4	.505	20.	164.	91.	27.	23.	656.	752.	653.	747.	30842.	1091.	31932.	.0	.295	1429.

7.0	.8	6.3	.506	21.	195.	105.	28.	24.	658.	754.	653.	747.	30823.	1116.	31940.	.0	.295	1449.
8.0	.8	6.3	.507	22.	226.	119.	29.	25.	660.	755.	653.	748.	30802.	1141.	31943.	.0	.295	1471.
9.0	.8	6.2	.508	23.	255.	134.	30.	26.	662.	757.	653.	748.	30776.	1166.	31942.	.0	.295	1496.
10.0	.8	6.1	.509	24.	283.	148.	31.	27.	665.	758.	653.	748.	30745.	1192.	31937.	.0	.295	1523.
11.0	.9	6.0	.510	25.	311.	161.	32.	28.	668.	759.	653.	748.	30707.	1220.	31927.	.0	.295	1554.
12.0	.9	5.8	.511	26.	336.	175.	33.	29.	671.	761.	653.	748.	30666.	1248.	31914.	.0	.295	1584.
13.0	.9	5.7	.512	27.	360.	188.	34.	30.	674.	762.	653.	748.	30648.	1277.	31925.	.0	.295	1612.
14.0	.9	5.5	.514	28.	383.	201.	35.	31.	677.	763.	653.	748.	30626.	1308.	31933.	.0	.295	1650.
15.0	1.0	5.3	.515	29.	404.	214.	36.	32.	681.	764.	653.	748.	30595.	1341.	31936.	.0	.295	1688.
16.0	1.0	5.0	.517	30.	424.	227.	37.	33.	684.	765.	653.	748.	30559.	1372.	31931.	.0	.295	1728.
critical wall temperature reached																		
17.0	1.0	5.0	.518	31.	441.	240.	38.	34.	688.	767.	653.	748.	30514.	1406.	31920.	.0	.295	1766.
18.0	1.0	4.7	.519	33.	458.	252.	39.	36.	691.	768.	653.	749.	30468.	1442.	31910.	.0	.295	1801.
19.0	1.1	4.5	.520	34.	472.	264.	40.	37.	694.	769.	653.	749.	30445.	1479.	31924.	.0	.295	1835.
20.0	1.1	4.4	.522	35.	486.	276.	42.	38.	697.	770.	653.	749.	30415.	1516.	31931.	.0	.295	1874.
21.0	1.2	4.2	.524	36.	497.	287.	43.	39.	700.	771.	653.	749.	30376.	1556.	31931.	.0	.295	1910.
22.0	1.2	4.1	.525	37.	508.	299.	44.	40.	703.	772.	653.	749.	30329.	1597.	31926.	.0	.295	1946.
23.0	1.2	3.9	.527	39.	517.	310.	45.	42.	705.	773.	653.	749.	30278.	1637.	31915.	.0	.295	1979.
24.0	1.3	3.8	.528	40.	526.	320.	46.	43.	708.	774.	653.	749.	30218.	1680.	31898.	.0	.295	2011.
25.0	1.3	3.7	.530	41.	533.	330.	48.	44.	710.	775.	653.	749.	30163.	1726.	31889.	.0	.295	2032.
26.0	1.3	3.6	.532	42.	540.	340.	49.	45.	711.	776.	653.	749.	30133.	1771.	31904.	.0	.295	2060.
27.0	1.4	3.6	.534	44.	545.	349.	50.	47.	713.	777.	653.	750.	30096.	1820.	31915.	.0	.295	2088.
28.0	1.4	3.5	.536	45.	550.	358.	52.	48.	715.	777.	653.	750.	30053.	1870.	31922.	.0	.295	2114.
29.0	1.5	3.4	.538	46.	555.	367.	53.	49.	716.	778.	653.	750.	30005.	1919.	31923.	.0	.295	2138.
30.0	1.5	3.4	.540	48.	559.	375.	54.	50.	717.	779.	653.	750.	29950.	1971.	31922.	.0	.295	2160.
31.0	1.6	3.3	.542	49.	562.	382.	55.	52.	718.	780.	653.	750.	29894.	2024.	31918.	.0	.295	2181.
32.0	1.6	3.3	.544	50.	565.	389.	57.	53.	719.	780.	653.	750.	29836.	2077.	31913.	.0	.295	2202.
33.0	1.7	3.3	.546	52.	568.	396.	58.	54.	720.	781.	653.	750.	29772.	2133.	31905.	.0	.295	2221.
34.0	1.7	3.2	.548	53.	570.	402.	59.	56.	721.	781.	653.	750.	29705.	2190.	31895.	.0	.295	2239.
35.0	1.8	3.2	.550	54.	572.	408.	61.	57.	721.	782.	653.	751.	29633.	2248.	31881.	.0	.295	2256.
36.0	1.8	3.2	.552	55.	574.	414.	62.	58.	722.	782.	653.	751.	29557.	2310.	31866.	.0	.295	2272.
37.0	1.9	3.1	.554	57.	576.	419.	63.	60.	722.	783.	653.	751.	29476.	2370.	31846.	.0	.295	2285.
38.0	1.9	3.1	.556	58.	577.	424.	65.	61.	723.	783.	653.	751.	29390.	2433.	31823.	.0	.295	2299.
AFTTAC model with fos = 1.600000																		
38.5	1.9	3.1	.557	59.	578.	426.	65.	62.	723.	783.	653.	751.	29348.	2463.	31823.	.0	.295	2304.
39.0	2.0	3.1	.558	59.	579.	428.	66.	62.	723.	784.	654.	751.	29299.	2500.	31799.	.0	.295	2311.
40.0	2.0	3.1	.553	60.	580.	432.	67.	63.	724.	784.	654.	751.	28967.	2561.	31528.	9.0	.295	2429.
41.0	2.0	3.1	.543	60.	581.	436.	67.	63.	724.	784.	654.	751.	28427.	2620.	31047.	9.0	.295	2426.
42.0	2.0	3.1	.533	60.	582.	440.	67.	63.	724.	785.	654.	751.	27889.	2679.	30568.	8.9	.295	2413.



tank model with jacket.OUT

43.0	2.0	3.0	.523	60.	583.	443.	67.	63.	725.	785.	654.	751.	27353.	2738.	30091.	8.9	.295	2402.
44.0	2.0	3.0	.512	60.	584.	447.	67.	63.	725.	785.	654.	751.	26820.	2797.	29617.	8.9	.295	2390.
45.0	2.0	3.0	.502	60.	585.	450.	67.	63.	725.	786.	654.	751.	26290.	2855.	29145.	8.8	.295	2377.
46.0	2.0	3.0	.492	60.	586.	454.	63.	63.	726.	786.	653.	751.	25762.	2913.	28675.	8.8	.295	2368.
47.0	2.0	3.0	.482	60.	587.	457.	63.	63.	726.	786.	653.	751.	25236.	2970.	28207.	8.7	.295	2360.
48.0	2.0	3.0	.472	60.	588.	460.	63.	63.	726.	786.	653.	751.	24712.	3028.	27740.	8.7	.295	2351.
49.0	2.0	3.0	.462	60.	589.	462.	63.	63.	726.	787.	653.	751.	24190.	3085.	27276.	8.7	.295	2342.
50.0	2.0	3.0	.452	60.	590.	465.	63.	63.	727.	787.	653.	751.	23671.	3142.	26813.	8.6	.295	2332.
51.0	2.0	2.9	.442	60.	591.	468.	63.	63.	727.	787.	653.	751.	23153.	3199.	26352.	8.6	.295	2322.
52.0	2.0	2.9	.433	60.	592.	470.	63.	63.	727.	787.	653.	751.	22638.	3255.	25893.	8.6	.295	2312.
53.0	2.0	2.9	.423	60.	592.	472.	63.	63.	728.	788.	653.	751.	22124.	3312.	25436.	8.5	.295	2301.
54.0	2.0	2.9	.413	60.	593.	475.	63.	63.	728.	788.	653.	751.	21614.	3368.	24981.	8.5	.295	2291.
55.0	2.0	2.9	.403	60.	594.	477.	63.	63.	728.	788.	653.	751.	21105.	3423.	24529.	8.4	.295	2279.
56.0	2.0	2.9	.394	60.	595.	479.	63.	63.	728.	788.	653.	751.	20600.	3479.	24079.	8.4	.295	2268.
57.0	2.0	2.9	.384	60.	596.	481.	63.	63.	728.	788.	653.	751.	20097.	3534.	23631.	8.4	.295	2256.
58.0	2.0	2.9	.374	60.	596.	483.	63.	63.	729.	789.	653.	751.	19596.	3589.	23185.	8.3	.295	2243.
59.0	2.0	2.9	.365	60.	597.	485.	63.	63.	729.	789.	653.	751.	19098.	3643.	22742.	8.3	.295	2231.
60.0	2.0	2.8	.355	60.	598.	487.	63.	63.	729.	789.	653.	751.	18604.	3698.	22301.	8.2	.295	2218.
61.0	2.0	2.8	.346	60.	599.	489.	63.	63.	729.	789.	653.	751.	18111.	3752.	21863.	8.2	.295	2205.
62.0	2.0	2.8	.337	60.	599.	491.	63.	63.	730.	789.	653.	751.	17622.	3805.	21428.	8.1	.295	2191.
63.0	2.0	2.8	.327	60.	600.	493.	63.	63.	730.	789.	653.	751.	17136.	3859.	20995.	8.1	.295	2178.
64.0	2.0	2.8	.318	60.	601.	494.	63.	63.	730.	790.	653.	751.	16653.	3912.	20565.	8.0	.295	2164.
65.0	2.0	2.8	.309	60.	602.	496.	63.	63.	730.	790.	653.	751.	16173.	3964.	20138.	8.0	.295	2150.
66.0	2.0	2.8	.300	60.	603.	498.	63.	63.	731.	790.	653.	751.	15697.	4017.	19713.	7.9	.295	2135.
67.0	2.0	2.8	.291	60.	603.	500.	63.	63.	731.	790.	653.	751.	15223.	4068.	19292.	7.9	.295	2120.
68.0	2.0	2.8	.282	60.	604.	502.	63.	63.	731.	790.	653.	751.	14753.	4120.	18873.	7.8	.295	2105.
69.0	2.0	2.8	.273	60.	605.	503.	63.	63.	731.	790.	653.	751.	14287.	4171.	18458.	7.7	.295	2090.
70.0	2.0	2.7	.264	60.	606.	505.	63.	63.	732.	790.	653.	751.	13824.	4222.	18046.	7.7	.295	2074.
71.0	2.0	2.7	.255	60.	607.	507.	63.	63.	732.	791.	653.	751.	13364.	4272.	17637.	7.6	.295	2058.
72.0	2.0	2.7	.247	60.	607.	509.	63.	63.	732.	791.	653.	751.	12908.	4322.	17231.	7.6	.295	2041.
73.0	2.0	2.7	.238	60.	608.	510.	63.	63.	732.	791.	653.	751.	12456.	4372.	16828.	7.5	.295	2024.
74.0	2.0	2.7	.229	60.	609.	512.	63.	63.	733.	791.	653.	751.	12008.	4421.	16429.	7.4	.295	2007.
75.0	2.0	2.7	.221	60.	610.	514.	63.	63.	733.	791.	653.	751.	11563.	4470.	16033.	7.4	.295	1989.
76.0	2.0	2.7	.212	60.	611.	516.	63.	63.	733.	791.	653.	751.	11123.	4518.	15641.	7.3	.295	1971.
77.0	2.0	2.7	.204	60.	612.	518.	63.	63.	734.	791.	653.	751.	10686.	4566.	15252.	7.2	.295	1953.
78.0	2.0	2.6	.196	60.	613.	519.	63.	63.	734.	792.	653.	751.	10254.	4613.	14867.	7.2	.295	1933.
79.0	2.0	2.6	.188	60.	614.	521.	63.	63.	734.	792.	653.	751.	9826.	4660.	14486.	7.1	.295	1914.
80.0	2.0	2.6	.180	60.	615.	523.	63.	63.	735.	792.	653.	751.	9402.	4707.	14109.	7.0	.295	1894.
81.0	2.0	2.6	.172	60.	616.	525.	63.	63.	735.	792.	653.	751.	8983.	4753.	13736.	6.9	.295	1873.

82.0	2.0	2.6	.164	60.	617.	527.	63.	63.	735.	792.	653.	751.	8569.	4798.	13367.	6.9	.295	1852.
83.0	2.0	2.6	.156	60.	618.	529.	63.	63.	736.	792.	653.	751.	8159.	4843.	13002.	6.8	.295	1830.
84.0	2.0	2.6	.148	60.	619.	531.	63.	63.	736.	793.	653.	751.	7755.	4888.	12642.	6.7	.295	1808.
85.0	2.0	2.5	.140	60.	620.	533.	63.	63.	736.	793.	653.	751.	7355.	4931.	12286.	6.6	.295	1785.
86.0	2.0	2.5	.133	60.	621.	535.	63.	63.	737.	793.	653.	751.	6960.	4975.	11935.	6.5	.295	1761.
87.0	2.0	2.5	.125	60.	622.	537.	63.	63.	737.	793.	653.	751.	6571.	5017.	11589.	6.4	.295	1737.
88.0	2.0	2.5	.118	60.	623.	539.	63.	63.	737.	793.	653.	751.	6188.	5059.	11247.	6.3	.295	1711.
89.0	2.0	2.5	.111	60.	625.	541.	63.	63.	738.	793.	653.	751.	5810.	5101.	10911.	6.2	.295	1684.
90.0	2.0	2.5	.104	60.	626.	543.	63.	63.	738.	794.	653.	751.	5438.	5142.	10580.	6.1	.295	1657.
91.0	2.0	2.4	.097	60.	627.	546.	63.	63.	739.	794.	653.	751.	5073.	5182.	10254.	6.0	.295	1628.
92.0	2.0	2.4	.090	60.	629.	548.	63.	63.	739.	794.	653.	751.	4714.	5221.	9935.	5.9	.295	1599.
93.0	2.0	2.4	.083	60.	630.	550.	63.	63.	740.	794.	653.	751.	4362.	5260.	9621.	5.8	.295	1568.
94.0	2.0	2.4	.077	60.	632.	553.	63.	63.	740.	794.	653.	751.	4016.	5298.	9314.	5.7	.295	1535.
95.0	2.0	2.4	.070	60.	633.	555.	63.	63.	741.	795.	653.	751.	3679.	5335.	9013.	5.6	.295	1501.
96.0	2.0	2.3	.064	60.	635.	558.	63.	63.	741.	795.	653.	751.	3349.	5371.	8719.	5.4	.295	1464.
97.0	2.0	2.3	.058	60.	636.	560.	63.	63.	742.	795.	653.	751.	3027.	5406.	8433.	5.3	.295	1426.
98.0	2.0	2.3	.052	60.	638.	563.	63.	63.	742.	795.	653.	751.	2714.	5440.	8154.	5.1	.295	1386.
99.0	2.0	2.3	.046	60.	640.	566.	63.	63.	743.	796.	653.	751.	2410.	5474.	7884.	5.0	.295	1343.
100.0	2.0	2.3	.040	60.	642.	569.	63.	63.	744.	796.	653.	751.	2117.	5506.	7623.	4.8	.295	1297.
101.0	2.0	2.2	.035	60.	644.	572.	63.	63.	744.	796.	653.	751.	1834.	5537.	7371.	4.6	.295	1247.
102.0	2.0	2.2	.030	60.	646.	575.	63.	63.	745.	796.	653.	751.	1562.	5567.	7129.	4.4	.295	1193.
103.0	2.0	2.2	.025	60.	648.	579.	63.	63.	746.	797.	653.	751.	1303.	5595.	6898.	4.2	.295	1134.
104.0	2.0	2.1	.020	60.	651.	582.	63.	63.	747.	797.	653.	751.	1058.	5622.	6680.	4.0	.295	1069.
104.0	2.0	2.1	.020	60.	651.	582.	63.	63.	747.	797.	653.	751.	1050.	5623.	6680.	4.0	.295	1066.

Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D              =      5.770000
tank volume (m^3)      =      122.357100
tank initial fill fraction =      2.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.310000
angle to defect top (deg) =      0.000000E+00
angle to defect bot (deg) =      90.000000
constant insulation conductance (W/m^2 K)=

```

22.700000

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twvd C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.200	16.	19.	20.	18.	18.	394.	389.	394.	389.	12368.	1584.	13953.	.0	.295	378.
2.0	.7	6.4	.200	17.	37.	31.	19.	19.	591.	619.	591.	618.	12338.	1614.	13951.	.0	.295	694.
3.0	.7	6.4	.200	18.	67.	46.	21.	21.	642.	712.	641.	710.	12291.	1656.	13947.	.0	.295	840.
4.0	.7	6.4	.199	19.	99.	61.	22.	22.	652.	741.	651.	738.	12243.	1702.	13945.	.0	.295	887.
5.0	.7	6.4	.199	20.	132.	76.	23.	23.	655.	749.	652.	745.	12195.	1751.	13946.	.0	.295	903.
6.0	.8	6.4	.199	21.	164.	91.	24.	24.	656.	752.	653.	747.	12148.	1806.	13954.	.0	.295	916.

7.0	.8	6.3	.199	22.	195.	106.	25.	25.	658.	754.	653.	747.	12100.	1862.	13962.	.0	.295	928.
8.0	.8	6.3	.199	24.	226.	120.	27.	27.	660.	755.	653.	748.	12052.	1918.	13970.	.0	.295	943.
9.0	.8	6.2	.199	25.	256.	134.	28.	28.	662.	757.	653.	748.	11999.	1978.	13978.	.0	.295	960.
10.0	.9	6.1	.199	26.	284.	148.	29.	29.	665.	758.	653.	748.	11943.	2040.	13983.	.0	.295	980.
11.0	.9	6.0	.199	27.	311.	162.	30.	30.	668.	759.	653.	748.	11881.	2101.	13982.	.0	.295	1001.
12.0	.9	5.8	.198	28.	337.	176.	31.	31.	671.	761.	653.	748.	11814.	2166.	13980.	.0	.295	1025.
13.0	1.0	5.7	.198	30.	362.	190.	33.	33.	674.	762.	653.	748.	11740.	2234.	13975.	.0	.295	1051.
14.0	1.0	5.5	.197	31.	385.	203.	34.	34.	678.	763.	653.	748.	11662.	2301.	13963.	.0	.295	1077.
15.0	1.0	5.2	.197	32.	406.	217.	35.	35.	681.	765.	653.	748.	11577.	2372.	13949.	.0	.295	1104.
16.0	1.1	5.0	.196	33.	426.	230.	36.	36.	685.	766.	653.	749.	11485.	2448.	13932.	.0	.295	1131.
critical wall temperature reached																		
17.0	1.1	4.9	.195	34.	444.	243.	37.	37.	688.	767.	653.	749.	11401.	2526.	13927.	.0	.295	1155.
18.0	1.1	4.7	.195	36.	460.	257.	39.	39.	692.	768.	653.	749.	11310.	2610.	13920.	.0	.295	1184.
19.0	1.2	4.5	.194	37.	475.	269.	40.	40.	695.	769.	653.	749.	11211.	2699.	13910.	.0	.295	1212.
20.0	1.2	4.3	.193	38.	489.	282.	41.	41.	698.	770.	653.	749.	11106.	2786.	13892.	.0	.295	1240.
21.0	1.3	4.2	.192	40.	501.	295.	43.	43.	701.	772.	653.	749.	10993.	2879.	13872.	.0	.295	1267.
22.0	1.3	4.0	.191	41.	512.	307.	44.	44.	704.	773.	653.	749.	10877.	2979.	13856.	.0	.295	1287.
23.0	1.4	3.9	.190	43.	522.	319.	45.	45.	707.	774.	653.	749.	10766.	3083.	13849.	.0	.295	1312.
24.0	1.4	3.8	.189	44.	531.	330.	47.	47.	709.	775.	653.	750.	10646.	3196.	13843.	.0	.295	1336.
25.0	1.4	3.6	.188	45.	539.	342.	48.	48.	711.	776.	653.	750.	10520.	3310.	13830.	.0	.295	1359.
26.0	1.5	3.5	.187	47.	546.	353.	50.	50.	713.	777.	653.	750.	10386.	3428.	13814.	.0	.295	1381.
27.0	1.5	3.5	.185	48.	552.	363.	51.	51.	715.	778.	653.	750.	10244.	3555.	13799.	.0	.295	1401.
28.0	1.6	3.4	.184	50.	558.	374.	53.	53.	717.	779.	653.	750.	10097.	3680.	13777.	.0	.295	1421.
29.0	1.6	3.3	.182	51.	563.	384.	54.	54.	718.	780.	653.	750.	9941.	3815.	13756.	.0	.295	1439.
30.0	1.7	3.3	.180	53.	568.	393.	56.	56.	720.	780.	653.	750.	9779.	3955.	13734.	.0	.295	1455.
31.0	1.8	3.2	.178	54.	572.	402.	57.	57.	721.	781.	653.	751.	9609.	4098.	13708.	.0	.295	1471.
32.0	1.8	3.1	.176	56.	576.	411.	58.	58.	722.	782.	653.	751.	9432.	4252.	13684.	.0	.295	1484.
33.0	1.9	3.1	.174	57.	579.	420.	60.	60.	723.	783.	653.	751.	9252.	4412.	13664.	.0	.295	1498.
AFTAC model with fos = 1.600000																		
33.7	1.9	3.1	.172	58.	582.	425.	61.	61.	724.	783.	653.	751.	9118.	4525.	13664.	.0	.295	1506.
34.0	1.9	3.1	.172	58.	582.	428.	61.	61.	724.	783.	653.	751.	9059.	4576.	13635.	.0	.295	1510.
35.0	2.0	3.0	.169	60.	585.	435.	63.	63.	725.	784.	653.	751.	8858.	4751.	13609.	.0	.295	1520.
36.0	2.0	3.0	.163	60.	588.	443.	63.	63.	726.	785.	653.	751.	8521.	4802.	13324.	5.9	.295	1596.
37.0	2.0	2.9	.156	60.	591.	450.	63.	63.	727.	785.	653.	751.	8166.	4841.	13008.	5.9	.295	1593.
38.0	2.0	2.9	.149	60.	593.	456.	63.	63.	728.	786.	653.	751.	7813.	4880.	12693.	5.9	.295	1587.
39.0	2.0	2.9	.142	60.	596.	463.	63.	63.	728.	787.	653.	751.	7460.	4919.	12379.	5.9	.295	1580.
40.0	2.0	2.8	.136	60.	598.	469.	63.	63.	729.	787.	653.	751.	7110.	4957.	12067.	5.8	.295	1573.
41.0	2.0	2.8	.129	60.	600.	475.	63.	63.	730.	788.	653.	751.	6761.	4995.	11757.	5.8	.295	1562.
42.0	2.0	2.8	.122	60.	603.	481.	63.	63.	730.	788.	653.	751.	6415.	5033.	11448.	5.8	.295	1551.



tank model with jacket.OUT

43.0	2.0	2.8	116	60.	605.	487.	63.	731.	789.	653.	751.	6071.	5071.	11142.	5.7	.295	1539.
44.0	2.0	2.7	109	60.	607.	492.	63.	732.	789.	653.	751.	5730.	5109.	10838.	5.7	.295	1526.
45.0	2.0	2.7	103	60.	609.	497.	63.	733.	790.	653.	751.	5392.	5146.	10538.	5.6	.295	1510.
46.0	2.0	2.7	097	60.	611.	502.	63.	733.	790.	653.	751.	5058.	5182.	10240.	5.5	.295	1493.
47.0	2.0	2.6	090	60.	613.	507.	63.	734.	790.	653.	751.	4728.	5218.	9946.	5.5	.295	1475.
48.0	2.0	2.6	084	60.	615.	512.	63.	735.	791.	653.	751.	4402.	5254.	9656.	5.4	.295	1455.
49.0	2.0	2.6	078	60.	617.	517.	63.	735.	791.	653.	751.	4081.	5289.	9370.	5.3	.295	1433.
50.0	2.0	2.6	072	60.	619.	521.	63.	736.	792.	653.	751.	3765.	5324.	9089.	5.2	.295	1409.
51.0	2.0	2.5	066	60.	622.	526.	63.	737.	792.	653.	751.	3454.	5358.	8812.	5.1	.295	1382.
52.0	2.0	2.5	060	60.	624.	530.	63.	737.	792.	653.	751.	3150.	5391.	8541.	5.0	.295	1355.
53.0	2.0	2.5	054	60.	626.	535.	63.	738.	793.	653.	751.	2852.	5424.	8276.	4.9	.295	1324.
54.0	2.0	2.4	049	60.	628.	539.	63.	739.	793.	653.	751.	2561.	5456.	8017.	4.8	.295	1290.
55.0	2.0	2.4	043	60.	630.	543.	63.	740.	794.	653.	751.	2278.	5487.	7765.	4.6	.295	1254.
56.0	2.0	2.4	038	60.	633.	548.	63.	740.	794.	653.	751.	2003.	5517.	7520.	4.5	.295	1215.
57.0	2.0	2.3	033	60.	635.	552.	63.	741.	794.	653.	751.	1737.	5546.	7284.	4.3	.295	1171.
58.0	2.0	2.3	028	60.	638.	556.	63.	742.	795.	653.	751.	1482.	5574.	7056.	4.2	.295	1124.
59.0	2.0	2.3	024	60.	640.	561.	63.	743.	795.	653.	751.	1238.	5601.	6839.	4.0	.295	1070.
59.8	2.0	2.2	020	60.	642.	564.	63.	744.	795.	653.	751.	1047.	5622.	6839.	3.8	.295	1023.

TMID effect of PRV setting



Tank Model with Insulation Defects (TMID v1.0)

input data

```

propane
fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      1.800000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)=      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.600000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	146.2	1.8	593.9	55.1	.190	14677.7
.0	20.0	140.7	1.8	593.9	55.1	.206	15620.8
.0	30.0	134.9	1.8	593.8	55.1	.225	16681.7
.0	40.0	128.8	1.8	593.9	55.1	.247	17767.8
.0	50.0	122.2	1.8	593.8	55.1	.275	18896.0
.0	60.0	115.4	1.8	593.9	55.1	.306	20497.7
.0	70.0	108.1	1.8	593.9	55.1	.342	22176.4
.0	80.0	101.1	1.8	593.9	55.1	.380	24096.0
.0	90.0	94.8	1.8	593.8	55.1	.415	26119.9
.0	100.0	91.6	1.8	593.9	55.1	.421	26365.2
.0	110.0	89.7	1.8	593.8	55.1	.417	26194.4
.0	120.0	88.0	1.8	593.9	55.1	.411	25563.7
.0	130.0	86.3	1.8	593.8	55.1	.407	25496.5
.0	140.0	84.7	1.8	593.9	55.1	.401	25448.2
.0	150.0	83.1	1.8	593.9	55.1	.396	24891.1
.0	160.0	81.8	1.8	593.9	55.1	.391	24990.8
.0	170.0	80.3	1.8	593.8	55.1	.386	24486.5
.0	180.0	79.1	1.8	593.9	55.1	.380	24059.1

# Tank Model with Insulation Defects (TMID v1.0)

## input data

```

fire temp (deg C)      =      816.000000
fire emissivity        =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.000000
tank L/D               =      5.800000
tank volume (m^3)      =      122.993300
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)   =      1.760000
surface emissivity     =      9.000000E-01
lading initial temp(deg C) =      16.000000
critical wall temp (deg C) =      427.000000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.400000
angle to defect top (deg) =      0.000000E+00
angle to defect bot (deg) =      180.000000
constant insulation conductance (W/m^2 K) =      22.700000
    
```

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twvd C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.7	6.4	.900	16.	19.	20.	17.	17.	394.	389.	394.	389.	55997.	198.	56195.	.0	.295	863.
2.0	.7	6.4	.902	17.	37.	31.	21.	19.	591.	619.	591.	618.	55997.	198.	56195.	.0	.295	2245.
3.0	.7	6.4	.905	18.	67.	46.	24.	21.	642.	712.	641.	710.	55997.	198.	56195.	.0	.295	2940.
4.0	.7	6.4	.908	19.	99.	61.	26.	22.	652.	741.	651.	738.	55998.	197.	56195.	.0	.295	3129.
5.0	.7	6.4	.912	20.	131.	75.	27.	23.	655.	749.	652.	745.	55999.	196.	56195.	.0	.295	3184.
6.0	.8	6.4	.915	22.	163.	90.	28.	25.	656.	752.	653.	747.	56000.	194.	56195.	.0	.295	3215.
7.0	.8	6.3	.919	23.	194.	104.	29.	26.	658.	754.	653.	747.	56003.	192.	56195.	.0	.295	3240.

tank model with jacket.OUT

8.0	.8	6.3	.923	24.	225.	118.	31.	27.	660.	755.	653.	748.	56006.	189.	56195.	.0	.295	3267.
9.0	.9	6.2	.927	25.	254.	132.	32.	28.	662.	757.	653.	748.	56009.	186.	56195.	.0	.295	3296.
10.0	.9	6.1	.931	27.	282.	145.	33.	30.	665.	758.	653.	748.	56014.	181.	56195.	.0	.295	3326.
11.0	.9	6.0	.935	28.	309.	158.	35.	31.	667.	759.	653.	748.	56019.	176.	56195.	.0	.295	3361.
12.0	1.0	5.9	.939	29.	334.	170.	36.	32.	670.	760.	653.	748.	56025.	170.	56195.	.0	.295	3396.
13.0	1.0	5.7	.944	31.	358.	183.	37.	34.	674.	761.	653.	748.	56032.	163.	56195.	.0	.295	3433.
14.0	1.0	5.5	.948	32.	380.	194.	39.	35.	677.	763.	653.	748.	56039.	155.	56195.	.0	.295	3468.
15.0	1.1	5.3	.953	34.	400.	206.	40.	36.	680.	764.	653.	749.	56048.	147.	56195.	.0	.295	3506.
16.0	1.1	5.1	.958	35.	419.	217.	41.	38.	683.	765.	653.	749.	56059.	136.	56195.	.0	.295	3546.
critical wall temperature reached																		
17.0	1.2	5.0	.963	36.	436.	228.	43.	39.	687.	766.	653.	749.	56071.	124.	56194.	.0	.295	3587.
18.0	1.2	4.8	.968	38.	451.	238.	44.	41.	690.	767.	653.	749.	56084.	110.	56194.	.0	.295	3625.
19.0	1.2	4.6	.973	39.	465.	248.	46.	42.	693.	767.	653.	749.	56100.	95.	56194.	.0	.295	3668.
20.0	1.3	4.5	.979	41.	477.	257.	47.	43.	696.	768.	653.	749.	56116.	78.	56194.	.0	.295	3707.
21.0	1.3	4.3	.985	42.	488.	266.	49.	45.	698.	769.	653.	749.	56136.	59.	56194.	.0	.295	3759.
22.0	1.4	4.2	.991	43.	498.	274.	50.	46.	701.	770.	653.	750.	56157.	37.	56194.	.0	.295	3817.
23.0	1.4	4.1	.997	45.	506.	282.	52.	48.	703.	771.	653.	750.	56182.	13.	56194.	.0	.295	3931.
24.0	1.5	6.41.000	47.	59.	52.	53.	53.	49.	666.	759.	653.	750.	56004.	0.	56004.	5.8	.295	4056.
25.0	1.5	6.41.000	48.	55.	51.	55.	55.	51.	655.	752.	653.	750.	55656.	0.	55656.	5.8	.295	4053.
26.0	1.6	6.41.000	50.	56.	52.	56.	56.	52.	654.	751.	653.	750.	55284.	0.	55284.	6.3	.295	4054.
27.0	1.6	6.41.000	51.	58.	54.	58.	58.	54.	653.	750.	653.	750.	54908.	0.	54908.	6.3	.295	4047.
28.0	1.7	6.41.000	53.	59.	55.	59.	59.	55.	653.	751.	653.	750.	54529.	0.	54529.	6.4	.295	4047.
29.0	1.8	6.4	.999	54.	61.	57.	61.	57.	653.	751.	653.	751.	54133.	1.	54134.	14.3	.295	4061.
30.0	1.8	6.4	.984	54.	91.	71.	61.	57.	654.	751.	653.	751.	53306.	78.	53384.	13.3	.295	3769.
31.0	1.8	6.4	.970	54.	124.	86.	61.	57.	655.	752.	653.	751.	52521.	151.	52672.	12.9	.295	3638.
32.0	1.8	6.4	.956	54.	156.	100.	61.	57.	656.	754.	653.	751.	51761.	221.	51982.	12.5	.295	3545.
33.0	1.8	6.4	.942	54.	187.	114.	61.	57.	658.	755.	653.	751.	51017.	290.	51307.	12.3	.295	3472.
34.0	1.8	6.3	.928	54.	218.	128.	61.	57.	660.	756.	653.	751.	50287.	358.	50645.	12.1	.295	3416.
35.0	1.8	6.2	.915	54.	248.	141.	61.	57.	662.	758.	653.	751.	49568.	424.	49992.	11.9	.295	3373.
36.0	1.8	6.1	.902	54.	276.	155.	61.	57.	664.	759.	653.	751.	48857.	490.	49347.	11.8	.295	3337.
37.0	1.8	6.0	.889	54.	303.	167.	61.	57.	667.	760.	653.	751.	48153.	555.	48709.	11.7	.295	3309.
38.0	1.8	5.9	.876	54.	329.	180.	61.	57.	670.	761.	653.	751.	47454.	620.	48074.	11.6	.295	3288.
39.0	1.8	5.7	.863	54.	353.	192.	61.	57.	673.	762.	653.	751.	46759.	685.	47444.	11.6	.295	3270.
40.0	1.8	5.5	.851	54.	376.	204.	61.	57.	676.	763.	653.	751.	46067.	749.	46816.	11.5	.295	3259.
41.0	1.8	5.3	.838	54.	397.	215.	61.	57.	680.	764.	653.	751.	45377.	813.	46190.	11.5	.295	3254.
42.0	1.8	5.1	.825	54.	416.	227.	61.	57.	683.	766.	653.	751.	44688.	877.	45565.	11.5	.295	3246.
43.0	1.8	5.1	.812	54.	434.	238.	61.	57.	686.	767.	653.	751.	44001.	940.	44941.	11.5	.295	3243.
44.0	1.8	4.8	.800	54.	450.	249.	61.	57.	690.	768.	653.	751.	43313.	1004.	44317.	11.5	.295	3245.
45.0	1.8	4.6	.787	54.	465.	259.	61.	57.	693.	769.	653.	751.	42626.	1068.	43693.	11.5	.295	3243.

46.0	1.8	4.5	.774	54.	478.	270.	61.	57.	696.	769.	653.	751.	41938.	1131.	43069.	11.5	.295	3244.
47.0	1.8	4.3	.762	54.	490.	280.	61.	57.	699.	770.	653.	751.	41250.	1195.	42445.	11.5	.295	3245.
48.0	1.8	4.2	.749	54.	500.	290.	61.	57.	701.	771.	653.	751.	40562.	1259.	41821.	11.5	.295	3246.
49.0	1.8	4.0	.736	54.	510.	299.	61.	57.	704.	772.	653.	751.	39874.	1323.	41197.	11.5	.295	3245.
50.0	1.8	3.9	.723	54.	518.	309.	61.	57.	706.	773.	653.	751.	39186.	1386.	40573.	11.5	.295	3246.
51.0	1.8	3.8	.711	54.	525.	318.	61.	57.	708.	774.	653.	751.	38499.	1450.	39949.	11.5	.295	3243.
52.0	1.8	3.7	.698	54.	532.	327.	61.	57.	709.	775.	653.	751.	37811.	1514.	39325.	11.5	.295	3242.
53.0	1.8	3.7	.685	54.	538.	335.	61.	57.	711.	775.	653.	751.	37125.	1578.	38702.	11.4	.295	3239.
54.0	1.8	3.6	.673	54.	543.	344.	61.	57.	713.	776.	653.	751.	36439.	1641.	38080.	11.4	.295	3233.
55.0	1.8	3.5	.660	54.	548.	352.	61.	57.	714.	777.	653.	751.	35754.	1705.	37458.	11.4	.295	3229.
56.0	1.8	3.5	.647	54.	552.	359.	61.	57.	715.	778.	653.	751.	35070.	1768.	36838.	11.4	.295	3223.
57.0	1.8	3.4	.635	54.	555.	367.	61.	57.	716.	778.	653.	751.	34387.	1831.	36219.	11.4	.295	3217.
58.0	1.8	3.4	.622	54.	559.	374.	61.	57.	717.	779.	653.	751.	33706.	1894.	35601.	11.3	.295	3209.
59.0	1.8	3.3	.610	54.	562.	381.	61.	57.	718.	779.	653.	751.	33027.	1957.	34984.	11.3	.295	3200.
60.0	1.8	3.3	.597	54.	564.	387.	61.	57.	719.	780.	653.	751.	32349.	2020.	34369.	11.3	.295	3193.
61.0	1.8	3.3	.585	54.	567.	394.	61.	57.	720.	781.	653.	751.	31674.	2083.	33756.	11.2	.295	3183.
62.0	1.8	3.2	.572	54.	569.	400.	61.	57.	720.	781.	653.	751.	31000.	2145.	33145.	11.2	.295	3172.
63.0	1.8	3.2	.560	54.	571.	406.	61.	57.	721.	782.	653.	751.	30329.	2207.	32536.	11.2	.295	3163.
64.0	1.8	3.2	.548	54.	573.	411.	61.	57.	722.	782.	653.	751.	29660.	2269.	31929.	11.1	.295	3151.
65.0	1.8	3.2	.535	54.	575.	417.	61.	57.	722.	783.	653.	751.	28993.	2331.	31324.	11.1	.295	3138.
66.0	1.8	3.1	.523	54.	577.	422.	61.	57.	723.	783.	653.	751.	28329.	2393.	30722.	11.0	.295	3126.
67.0	1.8	3.1	.511	54.	578.	427.	61.	57.	723.	784.	653.	751.	27668.	2454.	30122.	11.0	.295	3112.
68.0	1.8	3.1	.499	54.	580.	432.	61.	57.	724.	784.	653.	751.	27010.	2515.	29525.	10.9	.295	3100.
69.0	1.8	3.1	.487	54.	582.	436.	61.	57.	724.	784.	653.	751.	26354.	2576.	28930.	10.9	.295	3086.
70.0	1.8	3.0	.474	54.	583.	441.	61.	57.	725.	785.	653.	751.	25702.	2636.	28338.	10.8	.295	3072.
71.0	1.8	3.0	.462	54.	584.	445.	61.	57.	725.	785.	653.	751.	25052.	2696.	27749.	10.8	.295	3057.
72.0	1.8	3.0	.451	54.	586.	449.	61.	57.	725.	786.	653.	751.	24406.	2756.	27163.	10.7	.295	3040.
73.0	1.8	3.0	.439	54.	587.	453.	61.	57.	726.	786.	653.	751.	23764.	2816.	26580.	10.7	.295	3025.
74.0	1.8	3.0	.427	54.	589.	457.	61.	57.	726.	786.	653.	751.	23125.	2875.	26000.	10.6	.295	3008.
75.0	1.8	3.0	.415	54.	590.	461.	61.	57.	727.	787.	653.	751.	22489.	2934.	25423.	10.6	.295	2991.
76.0	1.8	2.9	.403	54.	591.	464.	61.	57.	727.	787.	653.	751.	21857.	2992.	24849.	10.5	.295	2973.
77.0	1.8	2.9	.392	54.	593.	468.	61.	57.	727.	787.	653.	751.	21229.	3051.	24279.	10.4	.295	2954.
78.0	1.8	2.9	.380	54.	594.	471.	61.	57.	728.	787.	653.	751.	20604.	3109.	23713.	10.4	.295	2936.
79.0	1.8	2.9	.369	54.	595.	475.	61.	57.	728.	788.	653.	751.	19984.	3166.	23150.	10.3	.295	2917.
80.0	1.8	2.9	.357	54.	597.	478.	61.	57.	729.	788.	653.	751.	19368.	3223.	22591.	10.2	.295	2897.
81.0	1.8	2.8	.346	54.	598.	481.	61.	57.	729.	788.	653.	751.	18756.	3280.	22036.	10.2	.295	2877.
82.0	1.8	2.8	.335	54.	599.	484.	61.	57.	730.	789.	653.	751.	18148.	3336.	21484.	10.1	.295	2857.
83.0	1.8	2.8	.324	54.	601.	487.	61.	57.	730.	789.	653.	751.	17545.	3392.	20937.	10.0	.295	2836.
84.0	1.8	2.8	.313	54.	602.	490.	61.	57.	730.	789.	653.	751.	16946.	3448.	20393.	9.9	.295	2814.



tank model with jacket.OUT

85.0	1.8	2.8	302	54.	603.	493.	61.	57.	731.	789.	653.	751.	16352.	3503.	19854.	9.9	.295	2792.
86.0	1.8	2.8	291	54.	605.	496.	61.	57.	731.	790.	653.	751.	15762.	3557.	19320.	9.8	.295	2769.
87.0	1.8	2.7	280	54.	606.	499.	61.	57.	732.	790.	653.	751.	15178.	3611.	18789.	9.7	.295	2746.
88.0	1.8	2.7	269	54.	607.	502.	61.	57.	732.	790.	653.	751.	14599.	3665.	18264.	9.6	.295	2721.
89.0	1.8	2.7	259	54.	609.	505.	61.	57.	733.	790.	653.	751.	14024.	3718.	17743.	9.5	.295	2696.
90.0	1.8	2.7	248	54.	610.	508.	61.	57.	733.	791.	653.	751.	13456.	3771.	17227.	9.4	.295	2671.
91.0	1.8	2.7	238	54.	612.	511.	61.	57.	733.	791.	653.	751.	12892.	3823.	16715.	9.3	.295	2645.
AFFTAC model with fos = 1.500000																		
92.0	1.8	2.6	228	54.	613.	514.	61.	57.	734.	791.	653.	751.	12344.	3874.	16715.	9.3	.295	2619.
92.0	1.8	2.6	228	54.	613.	514.	61.	57.	734.	791.	653.	751.	12334.	3875.	16209.	9.2	.295	2618.
93.0	1.8	2.6	217	54.	615.	517.	61.	57.	734.	791.	653.	751.	11783.	3926.	15709.	9.1	.295	2590.
94.0	1.8	2.6	207	54.	616.	519.	61.	57.	735.	792.	653.	751.	11237.	3977.	15213.	9.0	.295	2561.
95.0	1.8	2.6	197	54.	618.	522.	61.	57.	735.	792.	653.	751.	10697.	4027.	14723.	8.9	.295	2532.
96.0	1.8	2.6	188	54.	619.	525.	61.	57.	736.	792.	653.	751.	10163.	4076.	14239.	8.8	.295	2502.
97.0	1.8	2.5	178	54.	621.	528.	61.	57.	736.	792.	653.	751.	9636.	4125.	13761.	8.7	.295	2470.
98.0	1.8	2.5	168	54.	622.	531.	61.	57.	737.	793.	653.	751.	9116.	4173.	13290.	8.6	.295	2437.
99.0	1.8	2.5	159	54.	624.	534.	61.	57.	738.	793.	653.	751.	8603.	4221.	12824.	8.5	.295	2403.
100.0	1.8	2.5	149	54.	626.	537.	61.	57.	738.	793.	653.	751.	8097.	4268.	12365.	8.4	.295	2369.
101.0	1.8	2.4	140	54.	628.	540.	61.	57.	739.	793.	653.	751.	7599.	4314.	11913.	8.2	.295	2333.
102.0	1.8	2.4	131	54.	629.	543.	61.	57.	739.	794.	653.	751.	7109.	4359.	11468.	8.1	.295	2295.
103.0	1.8	2.4	122	54.	631.	547.	61.	57.	740.	794.	653.	751.	6626.	4404.	11030.	8.0	.295	2256.
104.0	1.8	2.4	113	54.	633.	550.	61.	57.	741.	794.	653.	751.	6153.	4448.	10601.	7.8	.295	2214.
105.0	1.8	2.3	105	54.	635.	553.	61.	57.	741.	794.	653.	751.	5688.	4491.	10179.	7.7	.295	2171.
106.0	1.8	2.3	096	54.	637.	556.	61.	57.	742.	795.	653.	751.	5232.	4533.	9766.	7.5	.295	2126.
107.0	1.8	2.3	088	54.	639.	560.	61.	57.	743.	795.	653.	751.	4787.	4574.	9361.	7.3	.295	2078.
108.0	1.8	2.3	080	54.	642.	563.	61.	57.	743.	795.	653.	751.	4352.	4615.	8966.	7.2	.295	2028.
109.0	1.8	2.2	072	54.	644.	567.	61.	57.	744.	796.	653.	751.	3927.	4654.	8581.	7.0	.295	1975.
110.0	1.8	2.2	065	54.	646.	571.	61.	57.	745.	796.	653.	751.	3514.	4692.	8207.	6.8	.295	1918.
111.0	1.8	2.2	057	54.	649.	575.	61.	57.	746.	796.	653.	751.	3114.	4729.	7844.	6.6	.295	1858.
112.0	1.8	2.1	050	54.	651.	579.	61.	57.	747.	797.	653.	751.	2727.	4765.	7492.	6.3	.295	1793.
113.0	1.8	2.1	043	54.	654.	583.	61.	57.	748.	797.	653.	751.	2354.	4800.	7154.	6.1	.295	1724.
114.0	1.8	2.1	037	54.	657.	587.	61.	57.	749.	797.	653.	751.	1997.	4833.	6830.	5.8	.295	1647.
115.0	1.8	2.0	030	54.	660.	592.	61.	57.	750.	798.	653.	751.	1656.	4865.	6521.	5.5	.295	1564.
116.0	1.8	2.0	025	54.	663.	596.	61.	57.	751.	798.	653.	751.	1334.	4894.	6229.	5.2	.295	1471.
116.8	1.8	1.9	020	54.	666.	600.	61.	57.	752.	798.	653.	751.	1087.	4917.	6229.	4.9	.295	1386.

TMID effect of surface emissivity



Tank Model with Insulation Defects (TMID v1.0)

input data

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propane
fire temp (deg C)      =      816.000000
fire emmissivity       =      1.000000
fire conv h (W/m^2K)   =      0.000000E+00
fire exposure frac     =      1.000000
tank D (m)             =      3.020000
tank L/D               =      5.770000
tank volume (m^3)      =      124.820600
tank initial fill fraction =      9.000000E-01
wall thick (mm)        =      17.500000
PRV operating P (MPa)  =      2.000000
surface emmissivity    =      8.000000E-01
lading initial temp(deg C) =      15.600000
jacket gap (mm)        =      13.000000
insul defect length (m) =      17.425400
constant insulation conductance (W/m^2 K)=      22.700000
  
```

at failure (burst pressure)/(tank pressure) = 1.600000

defect top (deg)	defect bot (deg)	fail time (min)	tank press (MPa)	vapour wall temp (deg C)	temp lading (deg C)	tank fill	lading mass (kg)
.0	10.0	117.3	2.0	570.0	60.0	.415	25665.6
.0	20.0	113.5	2.0	570.0	60.0	.432	26589.7
.0	30.0	109.4	2.0	570.0	60.0	.451	27461.5
.0	40.0	105.2	2.0	570.0	60.0	.474	28448.1
.0	50.0	100.6	2.0	570.0	60.0	.497	29720.9
.0	60.0	96.0	2.0	570.0	60.0	.521	31037.8
.0	70.0	91.8	2.0	570.0	60.0	.543	32003.1
.0	80.0	88.6	2.0	570.0	60.0	.555	32495.6
.0	90.0	87.2	2.0	570.0	60.0	.552	32181.3
.0	100.0	86.0	2.0	570.0	60.0	.546	32273.4
.0	110.0	85.0	2.0	570.1	60.0	.539	31964.0
.0	120.0	83.8	2.0	570.0	60.0	.533	31595.5
.0	130.0	82.9	2.0	570.0	60.0	.527	31332.8
.0	140.0	81.8	2.0	570.0	60.0	.520	31009.8
.0	150.0	80.9	2.0	570.0	60.0	.515	30796.8
.0	160.0	80.1	2.0	570.0	60.0	.508	30047.6
.0	170.0	79.1	2.0	570.0	60.0	.502	29776.6
.0	180.0	78.3	2.0	570.0	60.0	.496	29572.8

AFFTAC chlorine car

Tank Model with Insulation Defects (TMID v1.0)

input data

chlorine  
fire temp (deg C) = 816.000000  
fire emissivity = 1.000000  
fire conv h (W/m^2K) = 0.000000E+00  
fire exposure frac = 1.000000  
tank D (m) = 3.000000  
tank L/D = 5.770000  
tank volume (m^3) = 122.357100  
tank initial fill fraction = 9.000000E-01  
wall thick (mm) = 17.500000  
PRV operating P (MPa) = 2.000000  
surface emissivity = 9.000000E-01  
lading initial temp(deg C) = 16.000000  
critical wall temp (deg C) = 215.000000  
jacket gap (mm) = 50.000000  
insul defect length (m) = 17.310000  
angle to defect top (deg) = 0.000000E+00  
angle to defect bot (deg) = 0.000000E+00  
temperature dependent insulation properties  
properties for KAOWOOL  
kaowool density (kg/m^3) = 72.000000

time (min)	press (MPa)	pbst (MPa)	fill C	tlad C	twld C	twvi C	twli C	twld C	tjvd C	tjvi C	tjld C	tjli C	mliq kg	mvap kg	mtot kg	mdot kg/s	kins W/mK	qdottot kW
1.0	.5	6.4	.900	16.	19.	16.	16.	16.	394.	411.	394.	411.	156865.	231.157096.	231.157096.	.0	.072	54.
2.0	.5	6.4	.900	16.	37.	17.	16.	16.	591.	672.	590.	672.	156859.	231.157090.	231.157090.	.0	.125	185.
3.0	.5	6.4	.900	16.	67.	19.	17.	17.	642.	773.	641.	773.	156859.	231.157090.	231.157090.	.0	.149	275.
4.0	.5	6.4	.901	16.	99.	22.	17.	17.	652.	799.	651.	799.	156861.	231.157093.	231.157093.	.0	.155	307.

5.0	.5	6.4	.901	16.	131.	24.	17.	655.	805.	652.	805.156857.	231.157089.	.0	.157	315.
6.0	.5	6.4	.901	16.	163.	26.	17.	656.	806.	652.	806.156854.	232.157085.	.0	.157	317.
7.0	.5	6.3	.901	17.	194.	29.	17.	658.	806.	652.	806.156850.	232.157081.	.0	.157	318.
critical wall temperature reached															
8.0	.5	6.3	.902	17.	224.	31.	17.	660.	807.	652.	806.156845.	232.157077.	.0	.157	319.
9.0	.5	6.2	.902	17.	253.	33.	17.	662.	807.	652.	806.156842.	232.157074.	.0	.157	319.
10.0	.5	6.1	.902	17.	281.	36.	17.	665.	807.	652.	806.156838.	232.157070.	.0	.158	320.
11.0	.5	6.0	.903	17.	307.	38.	18.	667.	807.	652.	806.156834.	232.157066.	.0	.158	320.
12.0	.5	5.9	.903	17.	332.	40.	18.	670.	807.	652.	806.156830.	232.157063.	.0	.158	321.
13.0	.5	5.7	.903	17.	355.	43.	18.	673.	807.	652.	806.156827.	232.157059.	.0	.158	321.
14.0	.5	5.5	.903	17.	377.	45.	18.	676.	807.	652.	806.156824.	233.157056.	.0	.158	322.
15.0	.5	5.3	.904	18.	396.	47.	18.	680.	807.	652.	806.156821.	233.157054.	.0	.158	323.
16.0	.5	5.1	.904	18.	415.	49.	18.	683.	807.	652.	806.156818.	233.157051.	.0	.158	324.
17.0	.5	5.1	.904	18.	431.	51.	18.	686.	807.	652.	806.156814.	233.157047.	.0	.158	324.
18.0	.5	4.9	.905	18.	446.	54.	18.	689.	807.	652.	806.156810.	233.157043.	.0	.158	324.
19.0	.5	4.7	.905	18.	459.	56.	19.	692.	807.	652.	806.156807.	233.157040.	.0	.158	325.
20.0	.5	4.6	.905	18.	471.	58.	19.	694.	807.	652.	806.156804.	233.157037.	.0	.158	326.
21.0	.5	4.4	.906	18.	482.	60.	19.	697.	807.	652.	806.156800.	233.157033.	.0	.158	326.
22.0	.5	4.3	.906	18.	491.	62.	19.	699.	807.	652.	806.156796.	234.157030.	.0	.158	327.
23.0	.5	4.2	.906	19.	499.	64.	19.	701.	807.	652.	806.156793.	234.157026.	.0	.158	327.
24.0	.5	4.1	.906	19.	506.	66.	19.	703.	807.	652.	806.156789.	234.157023.	.0	.158	328.
25.0	.5	4.0	.907	19.	512.	68.	19.	705.	807.	652.	806.156784.	234.157018.	.0	.158	329.
26.0	.6	3.9	.907	19.	518.	70.	19.	706.	807.	652.	806.156780.	234.157014.	.0	.158	329.
27.0	.6	3.9	.907	19.	523.	73.	19.	707.	807.	652.	806.156777.	234.157011.	.0	.158	330.
28.0	.6	3.8	.908	19.	527.	75.	20.	708.	807.	653.	806.156773.	234.157007.	.0	.158	331.
29.0	.6	3.8	.908	19.	530.	76.	20.	709.	807.	653.	806.156769.	234.157003.	.0	.158	331.
30.0	.6	3.7	.908	19.	533.	78.	20.	710.	807.	653.	806.156764.	235.156999.	.0	.158	332.
31.0	.6	3.7	.908	20.	536.	80.	20.	711.	807.	653.	806.156760.	235.156995.	.0	.158	332.
32.0	.6	3.7	.909	20.	538.	82.	20.	712.	807.	653.	806.156756.	235.156991.	.0	.158	333.
33.0	.6	3.6	.909	20.	540.	84.	20.	712.	807.	653.	806.156752.	235.156987.	.0	.159	333.
34.0	.6	3.6	.909	20.	541.	86.	20.	713.	807.	653.	806.156749.	235.156984.	.0	.159	334.
35.0	.6	3.6	.910	20.	543.	88.	20.	713.	807.	653.	806.156745.	235.156980.	.0	.159	335.
36.0	.6	3.6	.910	20.	544.	90.	21.	713.	807.	653.	806.156741.	236.156976.	.0	.159	336.
37.0	.6	3.6	.910	20.	545.	92.	21.	714.	807.	653.	806.156736.	236.156972.	.0	.159	336.
38.0	.6	3.5	.910	20.	546.	94.	21.	714.	807.	653.	806.156729.	236.156965.	.0	.159	336.
39.0	.6	3.5	.910	20.	547.	95.	21.	714.	807.	653.	806.156721.	237.156958.	.0	.159	336.
40.0	.6	3.5	.910	21.	547.	97.	21.	714.	807.	653.	806.156714.	237.156951.	.0	.159	336.
41.0	.6	3.5	.910	21.	548.	99.	21.	714.	807.	653.	807.156706.	237.156944.	.0	.159	337.
42.0	.6	3.5	.910	21.	548.	101.	21.	715.	807.	653.	807.156698.	238.156936.	.0	.159	338.

tank model with jacket.OUT

43.0	.6	3.5	.910	21.	549.	102.	21.	715.	807.	653.	807.	156688.	238.	156927.	.0	.159	339.
44.0	.6	3.5	.911	21.	549.	104.	22.	715.	807.	653.	807.	156678.	239.	156917.	.0	.159	339.
45.0	.6	3.5	.911	21.	549.	106.	22.	715.	807.	653.	807.	156669.	239.	156908.	.0	.159	340.
46.0	.6	3.5	.911	21.	549.	107.	22.	715.	807.	653.	807.	156658.	240.	156898.	.0	.160	341.
47.0	.6	3.5	.911	22.	550.	109.	22.	715.	807.	653.	807.	156648.	240.	156888.	.0	.160	342.
48.0	.6	3.5	.911	22.	550.	111.	22.	715.	807.	653.	807.	156639.	240.	156879.	.0	.160	342.
49.0	.6	3.5	.911	22.	550.	112.	22.	715.	807.	653.	807.	156629.	241.	156869.	.0	.160	342.
50.0	.6	3.5	.911	22.	550.	114.	22.	715.	807.	653.	807.	156620.	241.	156862.	.0	.160	342.
51.0	.6	3.5	.911	22.	550.	116.	22.	715.	807.	653.	807.	156611.	242.	156852.	.0	.160	343.
52.0	.6	3.5	.912	22.	550.	117.	23.	715.	807.	653.	807.	156602.	242.	156844.	.0	.160	344.
53.0	.6	3.5	.912	22.	550.	119.	23.	715.	807.	653.	807.	156593.	243.	156835.	.0	.160	344.
54.0	.6	3.5	.912	22.	551.	120.	23.	715.	807.	653.	807.	156584.	243.	156827.	.0	.160	344.
55.0	.6	3.5	.912	23.	551.	122.	23.	715.	807.	653.	807.	156574.	243.	156818.	.0	.160	345.
56.0	.6	3.5	.912	23.	551.	123.	23.	715.	807.	653.	807.	156565.	244.	156809.	.0	.160	346.
57.0	.6	3.5	.912	23.	551.	125.	23.	715.	807.	653.	807.	156555.	244.	156799.	.0	.161	347.
58.0	.6	3.5	.912	23.	551.	126.	23.	715.	807.	653.	807.	156545.	245.	156789.	.0	.161	348.
59.0	.6	3.5	.912	23.	551.	128.	23.	715.	807.	653.	807.	156535.	245.	156780.	.0	.161	348.
60.0	.6	3.5	.912	23.	551.	129.	24.	715.	807.	653.	807.	156527.	246.	156773.	.0	.161	349.
61.0	.6	3.5	.913	23.	551.	130.	24.	715.	807.	653.	807.	156518.	246.	156764.	.0	.161	349.
62.0	.6	3.5	.913	23.	551.	132.	24.	715.	807.	653.	807.	156508.	247.	156755.	.0	.161	350.
63.0	.6	3.5	.913	24.	551.	133.	24.	715.	807.	653.	807.	156498.	247.	156746.	.0	.161	350.
64.0	.6	3.5	.913	24.	551.	135.	24.	715.	807.	653.	807.	156487.	248.	156735.	.0	.161	352.
65.0	.6	3.5	.913	24.	551.	136.	24.	715.	807.	653.	807.	156478.	248.	156726.	.0	.161	352.
66.0	.6	3.5	.913	24.	551.	137.	24.	715.	807.	653.	807.	156468.	249.	156717.	.0	.161	353.
67.0	.7	3.5	.913	24.	551.	139.	24.	715.	808.	653.	807.	156459.	249.	156708.	.0	.161	353.
68.0	.7	3.5	.913	24.	551.	140.	25.	715.	808.	653.	807.	156449.	249.	156699.	.0	.161	354.
69.0	.7	3.5	.913	24.	551.	141.	25.	715.	808.	653.	807.	156440.	250.	156690.	.0	.161	355.
70.0	.7	3.5	.913	24.	551.	142.	25.	715.	808.	653.	807.	156429.	251.	156679.	.0	.162	355.
71.0	.7	3.5	.913	25.	551.	144.	25.	715.	808.	653.	807.	156419.	251.	156670.	.0	.162	355.
72.0	.7	3.5	.914	25.	551.	145.	25.	715.	808.	653.	807.	156409.	252.	156660.	.0	.162	356.
73.0	.7	3.5	.914	25.	551.	146.	25.	715.	808.	653.	807.	156398.	252.	156650.	.0	.162	357.
74.0	.7	3.5	.914	25.	551.	147.	25.	715.	808.	653.	807.	156388.	253.	156641.	.0	.162	357.
75.0	.7	3.5	.914	25.	551.	148.	25.	715.	808.	653.	807.	156377.	253.	156630.	.0	.162	358.
76.0	.7	3.5	.914	25.	551.	150.	26.	715.	808.	653.	807.	156366.	254.	156620.	.0	.162	358.
77.0	.7	3.5	.914	25.	551.	151.	26.	715.	808.	653.	807.	156356.	254.	156610.	.0	.162	359.
78.0	.7	3.5	.914	25.	551.	152.	26.	715.	808.	653.	807.	156346.	255.	156601.	.0	.162	359.
79.0	.7	3.5	.914	26.	551.	153.	26.	715.	808.	653.	807.	156337.	255.	156592.	.0	.162	360.
80.0	.7	3.5	.914	26.	551.	154.	26.	716.	808.	653.	807.	156326.	256.	156582.	.0	.162	360.
81.0	.7	3.5	.914	26.	551.	155.	26.	716.	808.	653.	807.	156316.	256.	156572.	.0	.162	361.



82.0	.7	3.5	.915	26.	551.	156.	26.	716.	808.	653.	807.156307.	257.156564.	.0	.162	361.
83.0	.7	3.5	.915	26.	551.	157.	26.	716.	808.	653.	807.156297.	257.156554.	.0	.162	362.
84.0	.7	3.5	.915	26.	551.	158.	27.	716.	808.	653.	807.156286.	258.156544.	.0	.162	363.
85.0	.7	3.5	.915	26.	551.	159.	27.	716.	808.	653.	807.156277.	258.156536.	.0	.163	363.
86.0	.7	3.5	.915	26.	551.	160.	27.	716.	808.	653.	807.156268.	259.156526.	.0	.163	364.
87.0	.7	3.5	.915	27.	551.	161.	27.	716.	808.	653.	807.156257.	259.156516.	.0	.163	364.
88.0	.7	3.5	.915	27.	551.	162.	27.	716.	808.	653.	807.156246.	260.156506.	.0	.163	365.
89.0	.7	3.5	.915	27.	551.	163.	27.	716.	808.	653.	807.156234.	261.156494.	.0	.163	365.
90.0	.7	3.5	.915	27.	551.	164.	27.	716.	808.	653.	807.156223.	261.156484.	.0	.163	366.
91.0	.7	3.5	.915	27.	551.	165.	27.	716.	808.	653.	807.156212.	262.156474.	.0	.163	366.
92.0	.7	3.5	.916	27.	551.	166.	28.	716.	808.	653.	807.156202.	262.156464.	.0	.163	367.
93.0	.7	3.5	.916	27.	551.	167.	28.	716.	808.	653.	807.156191.	263.156454.	.0	.163	367.
94.0	.7	3.5	.916	27.	551.	168.	28.	716.	808.	653.	807.156180.	264.156444.	.0	.163	368.
95.0	.7	3.5	.916	28.	551.	169.	28.	716.	808.	653.	807.156169.	264.156434.	.0	.163	368.
96.0	.7	3.5	.916	28.	551.	170.	28.	716.	808.	653.	807.156158.	265.156423.	.0	.163	368.
97.0	.7	3.5	.916	28.	551.	171.	28.	716.	808.	653.	807.156148.	265.156413.	.0	.163	368.
98.0	.7	3.5	.916	28.	551.	171.	28.	716.	808.	653.	807.156138.	266.156404.	.0	.163	368.
99.0	.7	3.5	.916	28.	552.	172.	29.	716.	808.	653.	807.156127.	267.156394.	.0	.163	368.
100.0	.7	3.5	.916	28.	552.	173.	29.	716.	808.	653.	807.156116.	267.156383.	.0	.163	368.
101.0	.7	3.5	.916	28.	552.	174.	29.	716.	808.	653.	807.156104.	268.156372.	.0	.163	369.
102.0	.7	3.5	.917	28.	552.	175.	29.	716.	808.	653.	807.156093.	269.156362.	.0	.163	369.
103.0	.7	3.5	.917	29.	552.	175.	29.	716.	808.	653.	807.156081.	269.156351.	.0	.163	370.
104.0	.8	3.5	.917	29.	552.	176.	29.	716.	808.	653.	807.156070.	270.156340.	.0	.164	370.
105.0	.8	3.5	.917	29.	552.	177.	29.	716.	808.	653.	807.156058.	271.156329.	.0	.164	370.
106.0	.8	3.5	.917	29.	552.	178.	29.	716.	808.	653.	807.156044.	272.156316.	.0	.164	372.
107.0	.8	3.5	.917	29.	552.	178.	30.	716.	808.	653.	807.156032.	272.156304.	.0	.164	372.
108.0	.8	3.5	.917	29.	552.	179.	30.	716.	808.	653.	807.156020.	273.156293.	.0	.164	372.
109.0	.8	3.5	.917	29.	552.	180.	30.	716.	808.	653.	807.156007.	274.156281.	.0	.164	373.
110.0	.8	3.5	.917	30.	552.	180.	30.	716.	808.	653.	807.155996.	274.156271.	.0	.164	372.
111.0	.8	3.5	.917	30.	552.	181.	30.	716.	808.	653.	807.155984.	275.156259.	.0	.164	373.
112.0	.8	3.5	.918	30.	552.	182.	30.	716.	808.	653.	807.155971.	276.156247.	.0	.164	374.
113.0	.8	3.5	.918	30.	552.	182.	30.	716.	808.	653.	807.155959.	277.156236.	.0	.164	374.
114.0	.8	3.5	.918	30.	552.	183.	31.	716.	808.	653.	807.155947.	277.156224.	.0	.164	374.
115.0	.8	3.5	.918	30.	552.	184.	31.	716.	808.	653.	807.155935.	277.156212.	.0	.164	375.
116.0	.8	3.5	.918	30.	552.	184.	31.	716.	808.	653.	807.155924.	277.156201.	.0	.164	375.
117.0	.8	3.5	.919	30.	552.	185.	31.	716.	808.	653.	807.155912.	277.156188.	.0	.164	375.
118.0	.8	3.5	.919	31.	552.	185.	31.	716.	808.	653.	807.155901.	276.156178.	.0	.164	375.
119.0	.8	3.5	.919	31.	552.	186.	31.	716.	808.	653.	807.155890.	276.156167.	.0	.164	376.
120.0	.8	3.5	.920	31.	552.	187.	31.	716.	808.	653.	807.155876.	276.156152.	.0	.164	377.



tank model with jacket.OUT

121.0	.8	3.5	.920	31.	552.	187.	32.	32.	716.	808.	653.	807.155863.	276.156139.	.0	.164	377.
122.0	.8	3.5	.920	31.	552.	188.	32.	32.	716.	808.	653.	807.155851.	276.156126.	.0	.164	377.
123.0	.8	3.5	.920	31.	552.	188.	32.	32.	716.	808.	653.	807.155837.	276.156113.	.0	.164	378.
124.0	.8	3.5	.921	31.	552.	189.	32.	32.	716.	808.	653.	807.155824.	276.156099.	.0	.164	378.
125.0	.8	3.5	.921	32.	552.	189.	32.	32.	716.	808.	653.	807.155812.	276.156087.	.0	.164	378.
126.0	.8	3.5	.921	32.	552.	190.	32.	32.	716.	808.	653.	807.155799.	276.156074.	.0	.164	378.
127.0	.8	3.5	.921	32.	552.	190.	32.	32.	716.	808.	653.	807.155786.	275.156061.	.0	.164	379.
128.0	.8	3.5	.922	32.	552.	191.	32.	32.	716.	808.	653.	807.155773.	275.156048.	.0	.164	379.
129.0	.8	3.5	.922	32.	552.	191.	33.	33.	716.	808.	653.	807.155758.	275.156033.	.0	.164	379.
130.0	.8	3.5	.922	32.	552.	192.	33.	33.	716.	808.	653.	807.155744.	275.156019.	.0	.164	380.
131.0	.8	3.5	.922	32.	552.	192.	33.	33.	716.	808.	653.	807.155731.	275.156006.	.0	.165	381.
132.0	.8	3.5	.923	33.	552.	193.	33.	33.	716.	808.	653.	807.155718.	275.155993.	.0	.165	381.
133.0	.8	3.5	.923	33.	552.	193.	33.	33.	716.	808.	653.	807.155704.	275.155979.	.0	.165	381.
134.0	.8	3.5	.923	33.	552.	194.	33.	33.	716.	808.	653.	807.155691.	275.155966.	.0	.165	381.
135.0	.8	3.5	.924	33.	552.	194.	33.	33.	716.	808.	653.	807.155674.	275.155949.	.0	.165	382.
136.0	.9	3.5	.924	33.	552.	195.	34.	34.	716.	808.	653.	807.155661.	274.155936.	.0	.165	382.
137.0	.9	3.5	.924	33.	552.	195.	34.	34.	716.	808.	653.	807.155649.	274.155924.	.0	.165	382.
138.0	.9	3.5	.924	33.	552.	195.	34.	34.	716.	808.	653.	807.155635.	274.155909.	.0	.165	382.
139.0	.9	3.5	.925	33.	552.	196.	34.	34.	716.	808.	653.	807.155621.	274.155881.	.0	.165	382.
140.0	.9	3.5	.925	34.	552.	196.	34.	34.	716.	808.	653.	807.155607.	274.155866.	.0	.165	383.
141.0	.9	3.5	.925	34.	552.	197.	34.	34.	716.	808.	653.	807.155592.	274.155853.	.0	.165	383.
142.0	.9	3.5	.925	34.	552.	197.	34.	34.	716.	808.	653.	807.155579.	274.155839.	.0	.165	383.
143.0	.9	3.5	.926	34.	552.	197.	34.	34.	716.	808.	653.	807.155565.	274.155825.	.0	.165	384.
144.0	.9	3.5	.926	34.	552.	198.	35.	35.	716.	808.	653.	807.155551.	274.155810.	.0	.165	384.
145.0	.9	3.5	.926	34.	552.	198.	35.	35.	716.	808.	653.	807.155536.	274.155797.	.0	.165	384.
146.0	.9	3.5	.926	34.	552.	199.	35.	35.	716.	808.	653.	807.155523.	274.155783.	.0	.165	385.
147.0	.9	3.5	.927	35.	552.	199.	35.	35.	716.	808.	653.	807.155509.	274.155768.	.0	.165	385.
148.0	.9	3.5	.927	35.	552.	199.	35.	35.	716.	808.	653.	807.155495.	273.155753.	.0	.165	385.
149.0	.9	3.5	.927	35.	552.	200.	35.	35.	716.	808.	653.	807.155480.	273.155738.	.0	.165	385.
150.0	.9	3.5	.927	35.	552.	200.	35.	35.	716.	808.	653.	807.155465.	273.155724.	.0	.165	385.
151.0	.9	3.5	.928	35.	552.	200.	36.	36.	716.	808.	653.	807.155451.	273.155711.	.0	.165	385.
152.0	.9	3.5	.928	35.	552.	200.	36.	36.	716.	808.	653.	807.155438.	273.155697.	.0	.165	386.
153.0	.9	3.5	.928	35.	552.	201.	36.	36.	716.	808.	653.	807.155424.	273.155683.	.0	.165	386.
154.0	.9	3.5	.928	35.	552.	201.	36.	36.	716.	808.	653.	807.155410.	273.155669.	.0	.165	386.
155.0	.9	3.5	.929	36.	552.	201.	36.	36.	716.	808.	653.	807.155396.	273.155655.	.0	.165	386.
156.0	.9	3.5	.929	36.	552.	202.	36.	36.	716.	808.	653.	807.155382.	273.155642.	.0	.165	386.
157.0	.9	3.5	.929	36.	552.	202.	36.	36.	716.	808.	653.	807.155369.	273.155628.	.0	.165	386.
158.0	.9	3.5	.929	36.	552.	202.	36.	36.	716.	808.	653.	807.155355.	273.155612.	.0	.165	387.
159.0	.9	3.5	.930	36.	552.	203.	37.	37.	716.	808.	653.	807.155339.				

160.0	.9	3.5	.930	36.	552.	203.	37.	37.	716.	808.	653.	807.155326.	272.155598.	.0	.165	387.
161.0	.9	3.5	.930	36.	552.	203.	37.	37.	716.	808.	653.	807.155311.	272.155583.	.0	.165	387.
162.0	.9	3.5	.930	37.	552.	203.	37.	37.	716.	808.	653.	807.155297.	272.155569.	.0	.165	387.
163.0	.9	3.5	.931	37.	552.	204.	37.	37.	716.	808.	653.	807.155282.	272.155554.	.0	.165	388.
164.0	.9	3.5	.931	37.	552.	204.	37.	37.	716.	808.	653.	807.155267.	272.155539.	.0	.165	387.
165.0	1.0	3.5	.931	37.	552.	204.	37.	37.	716.	808.	653.	807.155252.	272.155525.	.0	.165	387.
166.0	1.0	3.5	.932	37.	552.	204.	38.	38.	716.	808.	653.	807.155238.	272.155510.	.0	.165	387.
167.0	1.0	3.5	.932	37.	552.	205.	38.	38.	716.	808.	653.	807.155223.	272.155495.	.0	.165	388.
168.0	1.0	3.5	.932	37.	552.	205.	38.	38.	716.	808.	653.	807.155207.	272.155479.	.0	.165	388.
169.0	1.0	3.5	.932	37.	552.	205.	38.	38.	716.	808.	653.	807.155190.	272.155462.	.0	.165	388.
170.0	1.0	3.5	.932	38.	552.	205.	38.	38.	716.	808.	653.	807.155175.	272.155447.	.0	.165	388.
171.0	1.0	3.5	.933	38.	552.	206.	38.	38.	716.	808.	653.	807.155160.	272.155431.	.0	.165	388.
172.0	1.0	3.5	.933	38.	552.	206.	38.	38.	716.	808.	653.	807.155144.	272.155415.	.0	.165	389.
173.0	1.0	3.5	.933	38.	552.	206.	38.	38.	716.	808.	653.	807.155126.	272.155398.	.0	.165	389.
174.0	1.0	3.5	.933	38.	552.	206.	39.	39.	716.	808.	653.	807.155108.	272.155380.	.0	.165	389.
175.0	1.0	3.5	.934	38.	552.	206.	39.	39.	716.	808.	653.	807.155094.	272.155365.	.0	.165	389.
176.0	1.0	3.5	.934	38.	552.	207.	39.	39.	716.	808.	653.	807.155078.	272.155349.	.0	.165	389.
177.0	1.0	3.5	.934	39.	552.	207.	39.	39.	716.	808.	653.	807.155062.	272.155333.	.0	.165	389.
178.0	1.0	3.5	.934	39.	552.	207.	39.	39.	716.	808.	653.	807.155046.	271.155318.	.0	.165	389.
179.0	1.0	3.5	.935	39.	552.	207.	39.	39.	716.	808.	653.	807.155030.	271.155301.	.0	.165	390.
180.0	1.0	3.5	.935	39.	552.	207.	39.	39.	716.	808.	653.	807.155013.	271.155284.	.0	.165	390.
181.0	1.0	3.5	.935	39.	552.	208.	40.	40.	716.	808.	653.	807.154997.	271.155268.	.0	.165	389.
182.0	1.0	3.5	.935	39.	552.	208.	40.	40.	716.	808.	653.	807.154981.	271.155252.	.0	.166	390.
183.0	1.0	3.5	.936	39.	552.	208.	40.	40.	716.	808.	653.	807.154965.	271.155236.	.0	.166	390.
184.0	1.0	3.5	.936	39.	552.	208.	40.	40.	716.	808.	653.	807.154949.	271.155220.	.0	.166	389.
185.0	1.0	3.5	.936	40.	552.	208.	40.	40.	716.	808.	653.	807.154933.	271.155204.	.0	.166	390.
186.0	1.0	3.5	.936	40.	552.	209.	40.	40.	716.	808.	653.	807.154916.	271.155187.	.0	.166	390.
187.0	1.0	3.5	.937	40.	552.	209.	40.	40.	716.	808.	653.	807.154898.	271.155170.	.0	.166	390.
188.0	1.0	3.5	.937	40.	552.	209.	40.	40.	716.	808.	653.	807.154881.	271.155152.	.0	.166	390.
189.0	1.0	3.5	.937	40.	552.	209.	41.	41.	716.	808.	653.	807.154864.	271.155135.	.0	.166	390.
190.0	1.0	3.5	.937	40.	552.	209.	41.	41.	716.	808.	653.	807.154845.	271.155116.	.0	.166	391.
191.0	1.0	3.5	.937	40.	552.	209.	41.	41.	716.	808.	653.	807.154828.	270.155098.	.0	.166	390.
192.0	1.0	3.5	.938	41.	552.	209.	41.	41.	716.	808.	653.	807.154810.	270.155080.	.0	.166	391.
193.0	1.0	3.5	.938	41.	552.	210.	41.	41.	716.	808.	653.	807.154793.	270.155063.	.0	.166	391.
194.0	1.0	3.5	.938	41.	552.	210.	41.	41.	716.	808.	653.	807.154775.	270.155044.	.0	.166	391.
195.0	1.1	3.5	.938	41.	552.	210.	41.	41.	716.	808.	653.	807.154756.	269.155026.	.0	.166	391.
196.0	1.1	3.5	.939	41.	552.	210.	42.	42.	716.	808.	653.	807.154737.	269.155007.	.0	.166	391.
197.0	1.1	3.5	.939	41.	552.	210.	42.	42.	716.	808.	653.	807.154720.	269.154989.	.0	.166	391.
198.0	1.1	3.5	.939	41.	552.	210.	42.	42.	716.	808.	653.	807.154700.	269.154969.	.0	.166	391.

tank model with jacket.OUT

199.0	1.1	3.5	.939	41.	552.	210.	42.	42.	716.	808.	653.	807.154681.	269.154950.	.0	.166	392.
200.0	1.1	3.5	.939	42.	552.	211.	42.	42.	716.	808.	653.	807.154663.	268.154932.	.0	.166	391.

AFFTAC ammonia car

DATA ENTERED INTO AFFTAC PROGRAM FOR ANALYSIS  
Program Version 2.0, October 20, 1997

## TANK PARAMETERS

Capacity (gal): 33000.  
Inside Diameter (ins.): 119.00  
Wall Thickness (ins.): .6900  
Tank Material Type: CARBON STEEL  
Tensile Strength of Tank Material (psi): 81000.  
Nominal Burst Strength (psig): 900.0  
Calculated Burst Strength (psig): 939.3  
Angle of Vent or Valve Orientation with Respect  
to Vertical (deg): .00

## PRODUCT DATA

Product Thermal Property Data Contained in Program  
Product Name: ANHYDROUS AMMONIA  
Product Type: Substance  
Initial Fraction of Tank Filled: .900  
Initial Temperature of Product: 60.00  
No Padding Gas Used

## SAFETY RELIEF DEVICE PARAMETERS

Safety Relief Valve Used  
Rated Flow Capacity (SCFM): 25000.  
Flow Rating Pressure (psig): 308.00  
Start-to-Discharge Pressure (psig): 280.50  
Vent or Valve Vapor Flow Discharge Coefficient: .80  
Vent or Valve Liquid Flow Discharge Coefficient: .80

## THERMAL PROTECTION SYSTEM CHARACTERISTICS

Jacketed Insulation System Not Resistant  
to High Temperature Effects  
Initial Conductance (BTU/hr-sq.ft-deg F): 4.00  
Time Interval for Linear Change from Initial Conductance  
to Steady State Conductance (min): .10

Discontinuities in Insulation Not Considered

No Tank Lining Used

## FIRE CONDITIONS

Standard Pool Fire Simulation Analysis  
Flame Temperature (deg F): 1500.0  
Fraction of Tank Surface Subject to Heat Input: 1.00  
Tank Radiation Emissivity Coefficient: .90

## ANALYSIS CONDITIONS

Time Limit (min): 200.00  
 Time Increment for Analysis (min): .10  
 Time Increments Between Display of Output Data: 10

 THERMAL PROPERTY DATA CONTAINED IN PROGRAM  
 FOR ANHYDROUS AMMONIA

Temperature (degrees F), Vapor Pressure (psia), Specific Heat (BTU/lb-deg F), Specific Volume (cu. ft/lb), Heat of Vaporization (BTU/lb), Compressibility Factor of Vapor, and Ratio of Specific Heats of Vapor

Temp.	Vapor Pres.	Spec. Heat	Spec. Volume	Heat of Vap.	Vapor Comp. Fact.	Vapor Ratio of Spec. Heats
-20.00	18.30	1.0600	.02369	583.6	.97	1.32
.00	30.42	1.0800	.02421	568.3	.95	1.32
20.00	48.21	1.1000	.02473	553.1	.94	1.32
40.00	73.32	1.1200	.02532	536.2	.92	1.32
60.00	107.60	1.1400	.02597	518.1	.90	1.32
80.00	153.00	1.1600	.02668	498.7	.87	1.32
100.00	211.90	1.1800	.02747	477.8	.84	1.32
120.00	286.40	1.2000	.02836	454.9	.82	1.32
140.00	379.10	1.2200	.02935	430.0	.79	1.32
160.00	492.85	1.2400	.03044	403.2	.76	1.32

MOLECULAR WEIGHT: 17.00



## PRODUCT: ANHYDROUS AMMONIA

TIME (min.)	TEMPERATURES (deg F)		PRESSURES		MASS FRACT. IN TANK	FILLED FRACT. OF TANK	RATE OF PRODUCT RELEASE (lbs/min)
	LIQ. PROD.	TANK VAPOR	WITHIN TANK (psi)	BURST STR. (psi)			
.0	60.0	60.0	92.9	939.3	1.000	.900	.0
1.0	61.3	105.9	95.2	939.2	1.000	.901	.0
2.0	62.7	154.1	97.9	939.0	1.000	.903	.0
3.0	64.1	201.4	100.7	938.5	1.000	.904	.0
4.0	65.5	247.6	103.6	937.4	1.000	.906	.0
5.0	66.8	292.7	106.6	935.6	1.000	.908	.0
6.0	68.2	336.5	109.7	932.8	1.000	.909	.0
7.0	69.6	379.0	112.8	928.8	1.000	.911	.0
8.0	71.1	419.9	116.0	923.5	1.000	.913	.0
9.0	72.5	459.3	119.3	916.7	1.000	.914	.0
10.0	73.9	497.1	122.7	908.3	1.000	.916	.0
11.0	75.3	533.1	126.1	898.3	1.000	.918	.0
12.0	76.8	567.4	129.7	886.7	1.000	.919	.0
13.0	78.2	599.9	133.3	873.6	1.000	.921	.0
14.0	79.6	630.6	137.0	859.1	1.000	.923	.0
15.0	81.1	659.5	140.8	843.3	1.000	.925	.0
16.0	82.6	686.6	144.7	826.6	1.000	.927	.0
17.0	84.0	711.9	148.7	809.0	1.000	.929	.0
18.0	85.5	735.5	152.8	790.8	1.000	.930	.0
19.0	87.0	757.5	157.0	772.3	1.000	.932	.0
20.0	88.5	777.8	161.3	753.7	1.000	.934	.0
21.0	90.0	796.5	165.7	735.1	1.000	.936	.0
22.0	91.5	813.8	170.1	740.1	1.000	.938	.0
23.0	93.0	829.6	174.7	722.7	1.000	.940	.0
24.0	94.6	844.1	179.4	706.7	1.000	.943	.0
25.0	96.1	857.4	184.2	692.1	1.000	.945	.0
26.0	97.6	869.5	189.0	678.9	1.000	.947	.0
27.0	99.2	880.4	194.0	666.8	1.000	.949	.0
28.0	100.7	890.4	199.0	655.8	1.000	.951	.0
29.0	102.3	899.4	204.2	645.9	1.000	.953	.0
30.0	103.8	907.6	209.5	637.0	1.000	.956	.0
31.0	105.4	914.9	214.9	628.9	1.000	.958	.0
32.0	106.9	921.5	220.4	621.6	1.000	.960	.0
33.0	108.5	927.5	226.1	615.1	1.000	.963	.0
34.0	110.1	932.8	231.9	609.3	1.000	.965	.0
35.0	111.7	937.5	237.8	604.1	1.000	.968	.0
36.0	113.2	941.7	243.8	599.4	1.000	.970	.0
37.0	114.8	945.5	250.0	595.3	1.000	.972	.0
38.0	116.4	948.8	256.3	591.7	1.000	.975	.0
39.0	118.0	951.7	262.7	588.5	1.000	.977	.0
40.0	119.6	954.3	269.3	585.6	1.000	.980	.0
41.0	121.2	956.5	276.0	583.2	1.000	.983	.0
42.0	122.7	958.4	282.6	581.1	1.000	.985	44.7
43.0	123.0	952.7	284.5	587.4	.996	.982	541.8

44.0	123.0	947.6	284.6	593.0	.992	.977	672.8
45.0	123.0	943.3	284.6	597.7	.987	.973	676.6
46.0	123.0	939.5	284.6	601.9	.983	.968	676.0
47.0	123.0	936.3	284.6	605.5	.979	.964	674.0
48.0	123.0	933.5	284.5	608.5	.974	.959	673.8
49.0	123.0	931.0	284.4	611.2	.970	.955	673.4
50.0	123.0	929.0	284.3	613.4	.965	.950	672.9
51.0	122.9	927.2	284.2	615.4	.961	.946	672.3
52.0	122.9	925.7	284.0	617.0	.957	.941	671.5
53.0	122.8	924.5	283.8	618.4	.952	.937	670.7
54.0	122.8	923.5	283.6	619.5	.948	.932	669.8
55.0	122.7	922.6	283.4	620.4	.943	.928	668.7
56.0	122.7	922.0	283.1	621.2	.939	.923	667.7
57.0	122.6	921.4	282.9	621.8	.935	.919	666.5
58.0	122.6	921.0	282.6	622.2	.930	.914	665.3
59.0	122.5	920.7	282.3	622.5	.926	.910	664.0
60.0	122.4	920.5	282.1	622.7	.922	.905	662.7
61.0	122.4	920.4	281.8	622.8	.917	.901	661.4
62.0	122.3	924.8	281.3	618.0	.913	.896	659.7
63.0	122.1	929.9	280.8	612.5	.909	.892	657.5
64.0	122.0	934.5	280.3	607.3	.904	.887	655.2
65.0	121.9	938.8	279.9	602.7	.900	.883	653.0
66.0	121.8	942.7	279.4	598.3	.896	.878	650.9
67.0	121.7	946.4	279.0	594.4	.892	.874	648.8
68.0	121.6	949.7	278.5	590.7	.887	.869	646.8
69.0	121.5	952.8	278.1	587.3	.883	.865	644.8
70.0	121.4	955.6	277.7	584.2	.879	.861	642.8
71.0	121.3	958.3	277.3	581.3	.875	.856	640.9
72.0	121.2	960.7	276.8	578.6	.871	.852	639.0
73.0	121.1	963.0	276.4	576.1	.867	.848	637.1
74.0	121.0	965.1	276.0	573.7	.862	.843	635.3
75.0	120.9	967.1	275.7	571.6	.858	.839	633.5
76.0	120.8	969.0	275.3	569.5	.854	.835	631.8
77.0	120.8	970.7	274.9	567.6	.850	.830	630.0
78.0	120.7	972.3	274.5	565.8	.846	.826	628.3
79.0	120.6	973.9	274.1	564.1	.842	.822	626.6
80.0	120.5	975.3	273.8	562.5	.838	.818	625.0
81.0	120.4	976.7	273.4	561.0	.834	.813	623.3
82.0	120.3	978.0	273.1	559.6	.830	.809	621.7
83.0	120.2	979.2	272.7	558.2	.826	.805	620.1
84.0	120.1	980.4	272.3	556.9	.821	.801	618.5
85.0	120.1	981.6	272.0	555.7	.817	.797	616.9
86.0	120.0	982.7	271.7	554.5	.813	.793	615.4
87.0	119.9	983.7	271.3	553.3	.809	.788	613.9
88.0	119.8	984.7	271.0	552.2	.805	.784	612.3
89.0	119.7	985.7	270.6	551.1	.801	.780	610.8
90.0	119.7	986.6	270.3	550.1	.797	.776	609.3
91.0	119.6	987.5	270.0	549.1	.793	.772	607.9
92.0	119.5	988.4	269.6	548.1	.790	.768	606.4
93.0	119.4	989.3	269.3	547.2	.786	.764	604.9
94.0	119.3	990.1	269.0	546.2	.782	.760	603.5

95.0	119.3	991.0	268.7	545.3	.778	.756	602.1
96.0	119.2	991.8	268.4	544.5	.774	.752	600.7
97.0	119.1	992.5	268.0	543.6	.770	.748	599.2
98.0	119.0	993.3	267.7	542.7	.766	.744	597.8
99.0	119.0	994.1	267.4	541.9	.762	.740	596.5
100.0	118.9	994.8	267.1	541.1	.758	.736	595.1
101.0	118.8	995.6	266.8	540.3	.754	.732	593.7
102.0	118.7	996.3	266.5	539.5	.750	.728	592.4
103.0	118.7	997.0	266.2	538.7	.747	.724	591.0
104.0	118.6	997.7	265.9	537.9	.743	.720	589.7
105.0	118.5	998.4	265.6	537.2	.739	.716	588.4
106.0	118.4	999.1	265.3	536.4	.735	.712	587.0
107.0	118.4	999.8	265.0	535.6	.731	.708	585.7
108.0	118.3	1000.5	264.7	534.9	.727	.704	584.4
109.0	118.2	1001.1	264.4	534.2	.724	.700	583.1
110.0	118.2	1001.8	264.1	533.4	.720	.696	581.8
111.0	118.1	1002.5	263.8	532.7	.716	.692	580.6
112.0	118.0	1003.1	263.5	532.0	.712	.688	579.3
113.0	117.9	1003.8	263.2	531.2	.708	.685	578.0
114.0	117.9	1004.4	262.9	530.5	.705	.681	576.8
115.0	117.8	1005.1	262.6	529.8	.701	.677	575.5
116.0	117.7	1005.7	262.3	529.1	.697	.673	574.3
117.0	117.7	1006.4	262.1	528.4	.693	.669	573.0
118.0	117.6	1007.0	261.8	527.7	.690	.665	571.8
119.0	117.5	1007.6	261.5	527.0	.686	.662	570.6
120.0	117.4	1008.3	261.2	526.3	.682	.658	569.4
121.0	117.4	1008.9	260.9	525.6	.678	.654	568.2
122.0	117.3	1009.5	260.6	524.9	.675	.650	566.9
123.0	117.2	1010.2	260.4	524.2	.671	.646	565.7
124.0	117.2	1010.8	260.1	523.5	.667	.643	564.6
125.0	117.1	1011.4	259.8	522.8	.664	.639	563.4
126.0	117.0	1012.1	259.5	522.2	.660	.635	562.2
127.0	117.0	1012.7	259.3	521.5	.656	.631	561.0
128.0	116.9	1013.3	259.0	520.8	.653	.628	559.8
129.0	116.8	1013.9	258.7	520.1	.649	.624	558.7
130.0	116.8	1014.5	258.4	519.4	.645	.620	557.5
131.0	116.7	1015.2	258.2	518.7	.642	.617	556.3
132.0	116.6	1015.8	257.9	518.1	.638	.613	555.2
133.0	116.6	1016.4	257.6	517.4	.635	.609	554.0
134.0	116.5	1017.0	257.4	516.7	.631	.605	552.9
135.0	116.4	1017.6	257.1	516.0	.627	.602	551.7
136.0	116.4	1018.8	256.8	514.8	.624	.598	550.6
137.0	116.3	1020.4	256.5	513.0	.620	.594	549.2
138.0	116.2	1021.9	256.1	511.4	.617	.591	547.8
139.0	116.1	1023.3	255.8	509.8	.613	.587	546.5
140.0	116.0	1024.6	255.5	508.3	.609	.584	545.2
141.0	116.0	1025.9	255.2	506.9	.606	.580	543.9
142.0	115.9	1027.1	254.9	505.6	.602	.576	542.6
143.0	115.8	1028.3	254.6	504.3	.599	.573	541.4
144.0	115.7	1029.4	254.4	503.1	.595	.569	540.2
145.0	115.7	1030.4	254.1	501.9	.592	.566	539.0

146.0	115.6	1031.5	253.8	500.8	.588	.562	537.9
147.0	115.5	1032.5	253.5	499.7	.585	.558	536.7
148.0	115.5	1033.4	253.3	498.7	.581	.555	535.6
149.0	115.4	1034.3	253.0	497.7	.578	.551	534.5
150.0	115.3	1035.2	252.7	496.7	.574	.548	533.4
151.0	115.3	1036.1	252.5	495.7	.571	.544	532.3
152.0	115.2	1036.9	252.2	494.8	.567	.541	531.2
153.0	115.1	1037.8	252.0	493.9	.564	.537	530.1
154.0	115.1	1038.6	251.7	493.0	.560	.534	529.1
155.0	115.0	1039.4	251.4	492.1	.557	.530	528.0
156.0	114.9	1040.2	251.2	491.3	.553	.527	526.9
157.0	114.9	1040.9	250.9	490.4	.550	.523	525.9
158.0	114.8	1041.7	250.7	489.6	.547	.520	524.8
159.0	114.8	1042.4	250.4	488.8	.543	.516	523.8
160.0	114.7	1043.1	250.2	488.0	.540	.513	522.7
161.0	114.6	1043.9	249.9	487.2	.536	.510	521.7
162.0	114.6	1044.6	249.7	486.4	.533	.506	520.7
163.0	114.5	1045.3	249.4	485.6	.530	.503	519.6
164.0	114.4	1046.0	249.2	484.8	.526	.499	518.6
165.0	114.4	1046.7	248.9	484.1	.523	.496	517.6
166.0	114.3	1047.4	248.7	483.3	.519	.492	516.5
167.0	114.2	1048.1	248.4	482.5	.516	.489	515.5
168.0	114.2	1048.8	248.2	481.8	.513	.486	514.5
169.0	114.1	1049.5	247.9	481.0	.509	.482	513.4
170.0	114.0	1050.1	247.6	480.3	.506	.479	512.4
171.0	114.0	1050.8	247.4	479.5	.503	.476	511.4
172.0	113.9	1051.5	247.1	478.8	.499	.472	510.3
173.0	113.9	1052.2	246.9	478.1	.496	.469	509.3
174.0	113.8	1052.8	246.7	477.3	.493	.466	506.4
175.0	113.8	1053.5	246.5	476.6	.489	.462	500.7
176.0	113.7	1054.2	246.4	475.8	.486	.459	497.3
177.0	113.7	1054.9	246.4	475.1	.483	.456	495.2
178.0	113.7	1055.5	246.4	474.4	.480	.453	493.7
179.0	113.7	1056.2	246.3	473.7	.476	.449	492.5
180.0	113.7	1056.8	246.3	472.9	.473	.446	491.4
181.0	113.7	1057.5	246.3	472.2	.470	.443	490.5
182.0	113.7	1058.2	246.2	471.5	.467	.440	489.5
183.0	113.7	1058.8	246.2	470.7	.464	.437	488.6
184.0	113.7	1059.5	246.2	470.0	.460	.433	487.7
185.0	113.7	1060.2	246.1	469.3	.457	.430	486.8
186.0	113.7	1060.8	246.1	468.6	.454	.427	485.9
187.0	113.7	1061.5	246.1	467.8	.451	.424	485.0
188.0	113.6	1062.1	246.1	467.1	.448	.421	484.0
189.0	113.6	1062.8	246.0	466.4	.445	.418	483.1
190.0	113.6	1063.5	246.0	465.7	.441	.414	482.2
191.0	113.6	1064.1	246.0	464.9	.438	.411	481.3
192.0	113.6	1064.8	245.9	464.2	.435	.408	480.3
193.0	113.6	1065.5	245.9	463.5	.432	.405	479.4
194.0	113.6	1066.1	245.9	462.7	.429	.402	478.5
195.0	113.6	1067.1	245.8	461.6	.426	.399	477.5
196.0	113.6	1068.8	245.7	459.7	.423	.396	474.8

197.0	113.5	1070.5	245.7	457.9	.420	.393	472.4
198.0	113.5	1072.0	245.7	456.2	.417	.390	471.1
199.0	113.5	1073.5	245.6	454.6	.413	.387	470.2
200.0	113.5	1074.9	245.6	453.1	.410	.383	469.5

## **Appendix F: Kaowool Insulation Properties**



# Thermal Ceramics



1185 Walkers Line  
Burlington, Ontario, Canada L7M 1L1  
(416) 335-3414 • FAX: (416) 335-5145

**FAX MESSAGE**DATE: April 10/92TO: Jane Ye  
Queens UniversityFROM: Sandy Ferguson(613)  
545-6489NUMBER OF PAGES TO FOLLOW: 4

Cop of Data Sheets on our  
Blanket & Strip.

Sandy.

**Thermal Ceramics**

A Division of Morganite Canada Corporation



# Thermal Ceramics

## Product Information

**Kaowool® Ceramic Fiber**

### KAOWOOL® BLANKET

- Available from stock in more than 40 different combinations of sizes and densities.
- Low thermal conductivity and heat storage.
- Resistant to thermal shock and chemical attack.
- Good acoustical and fire protection properties.
- Highly flexible; easily cut and fabricated.

Thermal Ceramics Kaowool Blanket is produced from Kaolin, a naturally occurring alumina, silica fire clay. The resultant high quality alumina-silica fibers are air-layed into a continuous mat and mechanically needled for added tensile strength and surface integrity.

#### Physical Properties

Color .....	White
Density, lbs./cu. ft. ....	3 - 12
Thickness, inches .....	¼ to 2
Maximum temperature rating, °F .....	2300
Melting point, °F .....	3200
Continuous use limit, up to °F .....	2000



#### Chemical Properties

Kaowool ceramic fiber Blanket products provide excellent resistance to chemical attack. Exceptions include hydrofluoric acid, phosphoric acid, and strong alkalis (i.e.  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ). Kaowool Blanket is unaffected by oil or water. Thermal and physical properties are restored after drying.

#### Chemical Analysis

(% weight basis, after firing)

Alumina .....	$\text{Al}_2\text{O}_3$ .....	45
Silica .....	$\text{SiO}_2$ .....	53
Ferric Oxide .....	$\text{Fe}_2\text{O}_3$ .....	1.0
Titanium Oxide .....	$\text{TiO}_2$ .....	1.7
Magnesium Oxide .....	$\text{MgO}$ .....	trace
Calcium Oxide .....	$\text{CaO}$ .....	0.1
Alkalies .....	$\text{Na}_2\text{O}$ .....	0.2
Boron Oxide .....	$\text{B}_2\text{O}_3$ .....	0.08

Water leachable elements on surface of fiber, maximum quantities, PPM

Boron .....	100
Chlorine .....	5
Fluorine .....	50
Sulphur .....	10

Ceramic Fiber • Insulating Firebrick • Refractory Castables and Monolithics • Mortars • Firebrick • Special Oxide Refractories

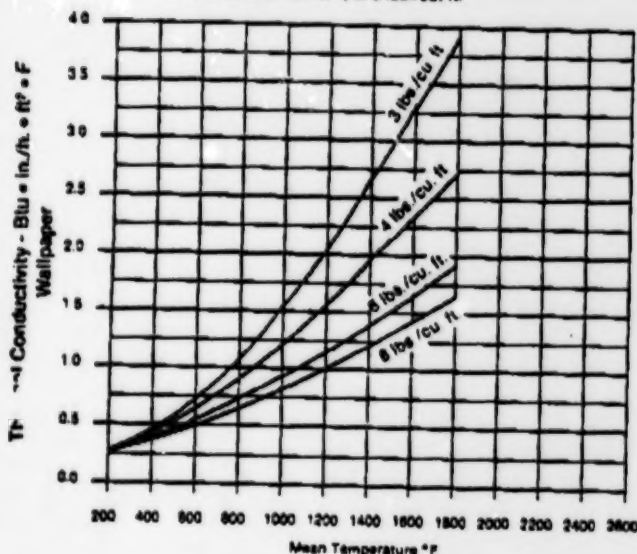
## Product Information

### Kaowool® Ceramic Fiber

#### Thermal Properties

Kaowool Blanket  
Thermal conductivity at various densities

Kaowool Blanket 3, 4, 6, 8 lbs./cu. ft.



**R Value:** The "R" value for ceramic fiber blanket is defined as the inverse of the "K" value multiplied by the thickness (inches). R value @ 70°F per ASTM C518-76 for 1", 6 lb/cu.ft. is 4.15/inch.

#### Typical Applications

Uses for Blanket include:

- Furnace kiln, reformer, and boiler linings
- Laboratory ovens
- Oven linings
- Furnace door linings and seals
- Furnace repair
- Annealing furnace linings
- Reheat furnace linings
- Investment casting mold wrap
- Heat relieving blankets usable steam and gas
- turbine insulation
- Soaking Pit Seals
- Expansion joint packing
- High temperature gasketing
- Fire protection
- Process Furnace linings
  - heaters
  - reformers
  - ethylene
- Acoustical service
- Cryogenic insulation

#### Standard Sizes

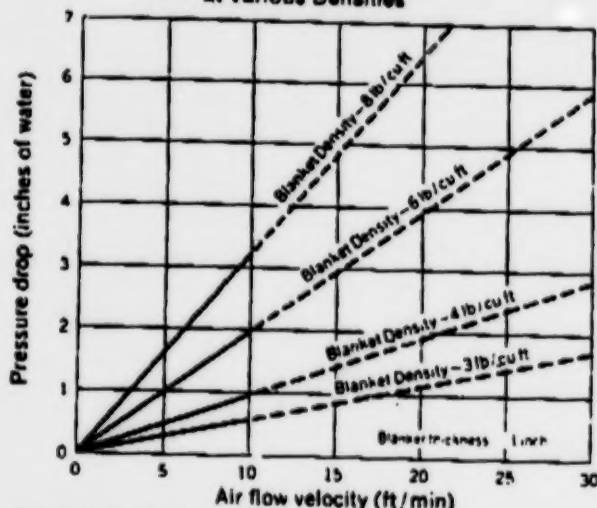
Kaowool Blanket is manufactured in the following thicknesses and sizes:

Standard Roll Sizes ..... 25' x 2', 25' x 4'  
Thickness, inches ..... 1/4, 1/2, 1, 1 1/2, 2  
Density, lbs./cu. ft. .... 3, 4, 6, 8, 10, 12

Note: not all densities available in all thicknesses

#### Special Testing

Pressure drop across Kaowool Blanket at Various Densities



#### Military Specifications & Approvals

Mil-1-23128A ..... 3, 6 lbs./cu. ft. blanket  
Mil-1-24244 ..... All blankets  
Mil-1-23128B ..... 6, 8 lbs./cu. ft. blanket

Non Combustibility Classification per UL723/ASTM-84 for all densities.

Flame Spread ..... 0  
Fuel Contribution ..... 0  
Smoke Developed ..... 0

#### Acoustical Performance Per ASTM C-423-84 A & E-795 Sound Absorption Coefficient

Kaowool Blanket	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
1"-4 lbs./cu.ft.	.29	1.00	1.04	.99	.98	.85
1"-6 lbs./cu.ft.	.50	.92	.91	.91	.94	.80
2"-4 lbs./cu.ft.	.92	1.01	1.01	1.03	1.10	1.00
2"-6 lbs./cu.ft.	.80	.72	.86	.92	1.02	.85

Refer to the Material Safety Data Sheet (MSDS) for Product Safety Information.



# Thermal Ceramics

## Product Information

### Kaowool® Ceramic Fiber

## KAOWOOL® STRIP

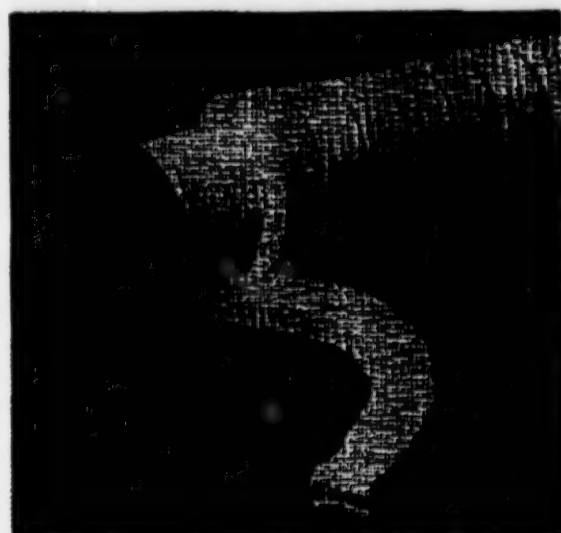
- Kaowool strip products are available in a wide variety of widths, thicknesses and densities.
- Available in all Kaowool fiber compositions.

Thermal Ceramics Kaowool strip products are cut from either Kaowool blanket, high purity blanket or Kaowool ZR blanket. These products are available in many forms and lengths depending upon the application. These strip products have low thermal conductivity, low heat storage capacity and are extremely resistant to thermal shock.

Kaowool ceramic fiber strip products are highly efficient insulators. These products have low shot content which allows more usable fiber for your insulating dollar. Kaowool strip products have longer fibers which give these products high tensile strength and resiliency to withstand vibration and physical abuse. Kaowool strip products are self-supporting and will not separate, sag or settle. Kaowool strip products have low thermal conductivity, low heat storage and are extremely resistant to thermal shock.

The wide variety of width, thicknesses densities, and Kaowool products that Kaowool strip is available in allows the user to select the proper product form for an application with a minimum of scrap and labor to install the Kaowool strip product.

Kaowool strip products have a wide variety of uses to include: packing strips for modules, expansion joints and gaskets.



### Physical Properties

	Blanket	High Purity	ZR
Color	White	White	White
Density, lbs./cu. ft.	3 - 8	3 - 8	6, 8
Thickness, inches	¼ to 2	¼ to 2	¼, 1
Maximum temperature rating, °F	2300	2300	2800
Melting point, °F	3200	3200	3200
Continuous use limit, up to °F	2000	2150	2400

### Chemical Analysis

(% weight basis, after firing)

	Blanket	High Purity	ZR
Alumina ..... $Al_2O_3$	45	47	32 - 36
Silica ..... $SiO_2$	53	53	45 - 48
Zirconia ..... $ZrO_2$	—	—	18 - 21
Ferric Oxide ..... $Fe_2O_3$	1.0	0.05	0.05 (0.15 max)
Titanium Oxide .. $TiO_2$	1.7	0.25 (0.4 max) trace inorganics	
Magnesium Oxide $MgO$	trace		
Calcium Oxide ... $CaO$	0.1		
Alkalies, as ..... $Na_2O$	0.2		
Boron Oxide ..... $B_2O_3$	0.08		

Water leachable elements on surface of fiber, maximum quantities, PPM

Boron .....	100
Chlorine .....	5
Fluorine .....	50
Sulphur .....	10

**Thermal Ceramics**

- Ceramic Fiber • Insulating Firebrick • Refractory Castables and Monolithics • Mortars • Firebrick • Special Oxide Refractories

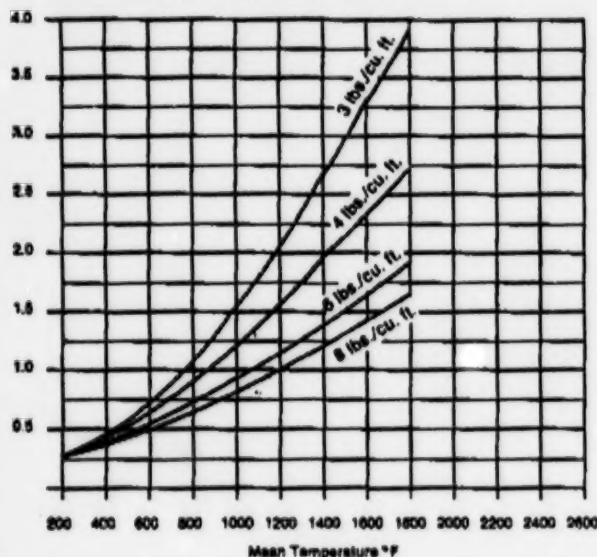
## Product Information

### Kaowool® Ceramic Fiber

#### Thermal Properties

Kaowool Standard blanket and High Purity blanket - Thermal conductivity at various densities

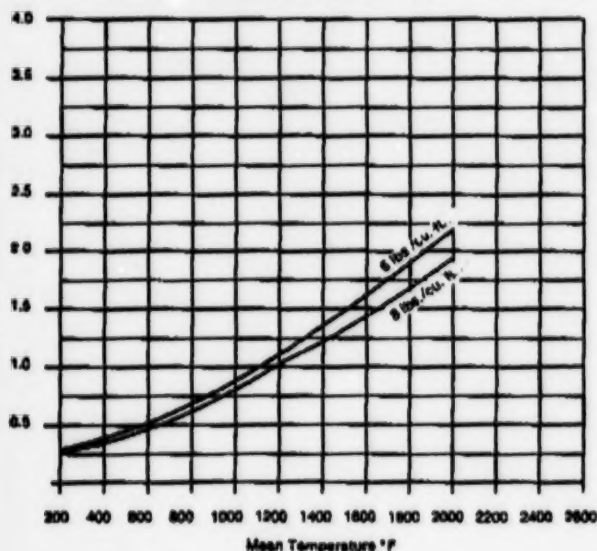
Standard and High Purity Blanket 3, 4, 6, 8 lbs./cu. ft.



**R Value:** The "R" value for ceramic fiber blanket is defined as the inverse of the "K" value multiplied by the thickness (inches). R value @ 70°F per ASTM C518-76 for 1", 6 lb/cu. ft. is 4.15/inch.

#### Kaowool ZR blanket Thermal Conductivity

Kaowool ZR Blanket 6 and 8 lbs./cu. ft.



#### Typical Applications

- Expansion joints
- High temperature filtration
- Gaskets
- Acoustical service for missiles, rockets and jet engines
- High temperature insulation
- Packing strips

#### Standard Sizes

Widths: 1" to 11"

Thickness: 1/4" - 2"

Densities: 3, 4, 6, 8 Lb per cu. ft.

*Handwritten notes:*

$R = \frac{1}{K} \times \text{thickness}$

$R = \frac{1}{1.2} \times 1 = 0.83$

$R = \frac{1}{1.4} \times 1 = 0.71$

$R = \frac{1}{1.6} \times 1 = 0.625$

$R = \frac{1}{1.8} \times 1 = 0.555$

$R = \frac{1}{2.0} \times 1 = 0.5$

$R = \frac{1}{2.2} \times 1 = 0.454$

$R = \frac{1}{2.4} \times 1 = 0.416$

$R = \frac{1}{2.6} \times 1 = 0.384$

$R = \frac{1}{2.8} \times 1 = 0.357$

$R = \frac{1}{3.0} \times 1 = 0.333$

$R = \frac{1}{3.2} \times 1 = 0.312$

$R = \frac{1}{3.4} \times 1 = 0.294$

$R = \frac{1}{3.6} \times 1 = 0.277$

$R = \frac{1}{3.8} \times 1 = 0.263$

$R = \frac{1}{4.0} \times 1 = 0.25$

$R = \frac{1}{4.2} \times 1 = 0.238$

$R = \frac{1}{4.4} \times 1 = 0.227$

$R = \frac{1}{4.6} \times 1 = 0.217$

$R = \frac{1}{4.8} \times 1 = 0.208$

$R = \frac{1}{5.0} \times 1 = 0.2$

$R = \frac{1}{5.2} \times 1 = 0.192$

$R = \frac{1}{5.4} \times 1 = 0.185$

$R = \frac{1}{5.6} \times 1 = 0.178$

$R = \frac{1}{5.8} \times 1 = 0.172$

$R = \frac{1}{6.0} \times 1 = 0.166$

$R = \frac{1}{6.2} \times 1 = 0.161$

$R = \frac{1}{6.4} \times 1 = 0.156$

$R = \frac{1}{6.6} \times 1 = 0.151$

$R = \frac{1}{6.8} \times 1 = 0.147$

$R = \frac{1}{7.0} \times 1 = 0.142$

$R = \frac{1}{7.2} \times 1 = 0.138$

$R = \frac{1}{7.4} \times 1 = 0.135$

$R = \frac{1}{7.6} \times 1 = 0.131$

$R = \frac{1}{7.8} \times 1 = 0.128$

$R = \frac{1}{8.0} \times 1 = 0.125$

$R = \frac{1}{8.2} \times 1 = 0.122$

$R = \frac{1}{8.4} \times 1 = 0.119$

$R = \frac{1}{8.6} \times 1 = 0.116$

$R = \frac{1}{8.8} \times 1 = 0.113$

$R = \frac{1}{9.0} \times 1 = 0.111$

$R = \frac{1}{9.2} \times 1 = 0.108$

$R = \frac{1}{9.4} \times 1 = 0.106$

$R = \frac{1}{9.6} \times 1 = 0.104$

$R = \frac{1}{9.8} \times 1 = 0.102$

$R = \frac{1}{10.0} \times 1 = 0.1$

$R = \frac{1}{10.2} \times 1 = 0.098$

$R = \frac{1}{10.4} \times 1 = 0.096$

$R = \frac{1}{10.6} \times 1 = 0.094$

$R = \frac{1}{10.8} \times 1 = 0.092$

$R = \frac{1}{11.0} \times 1 = 0.0909$

$R = \frac{1}{11.2} \times 1 = 0.0893$

$R = \frac{1}{11.4} \times 1 = 0.0877$

$R = \frac{1}{11.6} \times 1 = 0.0862$

$R = \frac{1}{11.8} \times 1 = 0.0847$

$R = \frac{1}{12.0} \times 1 = 0.0833$

$R = \frac{1}{12.2} \times 1 = 0.0819$

$R = \frac{1}{12.4} \times 1 = 0.0806$

$R = \frac{1}{12.6} \times 1 = 0.0794$

$R = \frac{1}{12.8} \times 1 = 0.0781$

$R = \frac{1}{13.0} \times 1 = 0.0769$

$R = \frac{1}{13.2} \times 1 = 0.0758$

$R = \frac{1}{13.4} \times 1 = 0.0746$

$R = \frac{1}{13.6} \times 1 = 0.0735$

$R = \frac{1}{13.8} \times 1 = 0.0725$

$R = \frac{1}{14.0} \times 1 = 0.0714$

$R = \frac{1}{14.2} \times 1 = 0.0704$

$R = \frac{1}{14.4} \times 1 = 0.0694$

$R = \frac{1}{14.6} \times 1 = 0.0685$

$R = \frac{1}{14.8} \times 1 = 0.0676$

$R = \frac{1}{15.0} \times 1 = 0.0667$

$R = \frac{1}{15.2} \times 1 = 0.0658$

$R = \frac{1}{15.4} \times 1 = 0.0649$

$R = \frac{1}{15.6} \times 1 = 0.0641$

$R = \frac{1}{15.8} \times 1 = 0.0633$

$R = \frac{1}{16.0} \times 1 = 0.0625$

$R = \frac{1}{16.2} \times 1 = 0.0617$

$R = \frac{1}{16.4} \times 1 = 0.0609$

$R = \frac{1}{16.6} \times 1 = 0.0602$

$R = \frac{1}{16.8} \times 1 = 0.0595$

$R = \frac{1}{17.0} \times 1 = 0.0588$

$R = \frac{1}{17.2} \times 1 = 0.0581$

$R = \frac{1}{17.4} \times 1 = 0.0574$

$R = \frac{1}{17.6} \times 1 = 0.0568$

$R = \frac{1}{17.8} \times 1 = 0.0562$

$R = \frac{1}{18.0} \times 1 = 0.0556$

$R = \frac{1}{18.2} \times 1 = 0.055$

$R = \frac{1}{18.4} \times 1 = 0.0544$

$R = \frac{1}{18.6} \times 1 = 0.0538$

$R = \frac{1}{18.8} \times 1 = 0.0532$

$R = \frac{1}{19.0} \times 1 = 0.0526$

$R = \frac{1}{19.2} \times 1 = 0.0521$

$R = \frac{1}{19.4} \times 1 = 0.0516$

$R = \frac{1}{19.6} \times 1 = 0.0511$

$R = \frac{1}{19.8} \times 1 = 0.0506$

$R = \frac{1}{20.0} \times 1 = 0.05$

$R = \frac{1}{20.2} \times 1 = 0.0495$

$R = \frac{1}{20.4} \times 1 = 0.049$

$R = \frac{1}{20.6} \times 1 = 0.0485$

$R = \frac{1}{20.8} \times 1 = 0.048$

$R = \frac{1}{21.0} \times 1 = 0.0476$

$R = \frac{1}{21.2} \times 1 = 0.0471$

$R = \frac{1}{21.4} \times 1 = 0.0466$

$R = \frac{1}{21.6} \times 1 = 0.0462$

$R = \frac{1}{21.8} \times 1 = 0.0457$

$R = \frac{1}{22.0} \times 1 = 0.0454$

$R = \frac{1}{22.2} \times 1 = 0.045$

$R = \frac{1}{22.4} \times 1 = 0.0446$

$R = \frac{1}{22.6} \times 1 = 0.0442$

$R = \frac{1}{22.8} \times 1 = 0.0438$

$R = \frac{1}{23.0} \times 1 = 0.0435$

$R = \frac{1}{23.2} \times 1 = 0.0431$

$R = \frac{1}{23.4} \times 1 = 0.0427$

$R = \frac{1}{23.6} \times 1 = 0.0423$

$R = \frac{1}{23.8} \times 1 = 0.0419$

$R = \frac{1}{24.0} \times 1 = 0.0417$

$R = \frac{1}{24.2} \times 1 = 0.0414$

$R = \frac{1}{24.4} \times 1 = 0.041$

$R = \frac{1}{24.6} \times 1 = 0.0407$

$R = \frac{1}{24.8} \times 1 = 0.0403$

$R = \frac{1}{25.0} \times 1 = 0.04$

$R = \frac{1}{25.2} \times 1 = 0.0396$

$R = \frac{1}{25.4} \times 1 = 0.0392$

$R = \frac{1}{25.6} \times 1 = 0.0389$

$R = \frac{1}{25.8} \times 1 = 0.0385$

$R = \frac{1}{26.0} \times 1 = 0.0381$

$R = \frac{1}{26.2} \times 1 = 0.0378$

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$R = \frac{1}{27.0} \times 1 = 0.0364$

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$R = \frac{1}{27.4} \times 1 = 0.0357$

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$R = \frac{1}{27.8} \times 1 = 0.035$

$R = \frac{1}{28.0} \times 1 = 0.0347$

$R = \frac{1}{28.2} \times 1 = 0.0344$

$R = \frac{1}{28.4} \times 1 = 0.034$

$R = \frac{1}{28.6} \times 1 = 0.0337$

$R = \frac{1}{28.8} \times 1 = 0.0334$

$R = \frac{1}{29.0} \times 1 = 0.0331$

$R = \frac{1}{29.2} \times 1 = 0.0327$

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$R = \frac{1}{29.6} \times 1 = 0.0321$

$R = \frac{1}{29.8} \times 1 = 0.0318$

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$R = \frac{1}{30.4} \times 1 = 0.0309$

$R = \frac{1}{30.6} \times 1 = 0.0306$

$R = \frac{1}{30.8} \times 1 = 0.0303$

$R = \frac{1}{31.0} \times 1 = 0.03$

$R = \frac{1}{31.2} \times 1 = 0.0297$

$R = \frac{1}{31.4} \times 1 = 0.0294$

$R = \frac{1}{31.6} \times 1 = 0.0291$

$R = \frac{1}{31.8} \times 1 = 0.0288$

$R = \frac{1}{32.0} \times 1 = 0.0285$

$R = \frac{1}{32.2} \times 1 = 0.0282$

$R = \frac{1}{32.4} \times 1 = 0.0279$

$R = \frac{1}{32.6} \times 1 = 0.0276$

$R = \frac{1}{32.8} \times 1 = 0.0273$

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$R = \frac{1}{33.4} \times 1 = 0.0264$

$R = \frac{1}{33.6} \times 1 = 0.0261$

$R = \frac{1}{33.8} \times 1 = 0.0258$

$R = \frac{1}{34.0} \times 1 = 0.0256$

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$R = \frac{1}{35.6} \times 1 = 0.0232$

$R = \frac{1}{35.8} \times 1 = 0.0229$

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$R = \frac{1}{36.2} \times 1 = 0.0223$

$R = \frac{1}{36.4} \times 1 = 0.022$

$R = \frac{1}{36.6} \times 1 = 0.0217$

$R = \frac{1}{36.8} \times 1 = 0.0214$

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$R = \frac{1}{37.2} \times 1 = 0.0208$

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$R = \frac{1}{37.8} \times 1 = 0.02$

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$R = \frac{1}{38.8} \times 1 = 0.0185$

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$R = \frac{1}{39.4} \times 1 = 0.0177$

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$R = \frac{1}{39.8} \times 1 = 0.0171$

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$R = \frac{1}{40.4} \times 1 = 0.0163$

$R = \frac{1}{40.6} \times 1 = 0.016$

$R = \frac{1}{40.8} \times 1 = 0.0157$

$R = \frac{1}{41.0} \times 1 = 0.0155$

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$R = \frac{1}{41.6} \times 1 = 0.0146$

$R = \frac{1}{41.8} \times 1 = 0.0143$

$R = \frac{1}{42.0} \times 1 = 0.0141$

$R = \frac{1}{42.2} \times 1 = 0.0138$

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$R = \frac{1}{42.6} \times 1 = 0.0132$

$R = \frac{1}{42.8} \times 1 = 0.0129$

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$R = \frac{1}{43.2} \times 1 = 0.0124$

$R = \frac{1}{43.4} \times 1 = 0.0121$

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$R = \frac{1}{44.4} \times 1 = 0.0107$

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$R = \frac{1}{44.8} \times 1 = 0.0101$

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$R = \frac{1}{45.4} \times 1 = 0.0093$

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$R = \frac{1}{45.8} \times 1 = 0.0087$

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$R = \frac{1}{47.6} \times 1 = 0.0062$

$R = \frac{1}{47.8} \times 1 = 0.0059$

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$R = \frac{1}{48.2} \times 1 = 0.0054$

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$R = \frac{1}{48.8} \times 1 = 0.0045$

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$R = \frac{1}{49.6} \times 1 = 0.0034$

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$R = \frac{1}{50.0} \times 1 = 0.0029$

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$R = \frac{1}{50.4} \times 1 = 0.0023$

$R = \frac{1}{50.6} \times 1 = 0.002$

$R = \frac{1}{50.8} \times 1 = 0.0017$

$R = \frac{1}{51.0} \times 1 = 0.0015$

$R = \frac{1}{51.2} \times 1 = 0.0012$

$R = \frac{1}{51.4} \times 1 = 0.0009$

$R = \frac{1}{51.6} \times 1 = 0.0006$

$R = \frac{1}{51.8} \times 1 = 0.0003$

$R = \frac{1}{52.0} \times 1 = 0.0001$

$R = \frac{1}{52.2} \times 1 = 0.0001$

$R = \frac{1}{52.4} \times 1 = 0.0001$

$R = \frac{1}{52.6} \times 1 = 0.0001$

$R = \frac{1}{52.8} \times 1 = 0.0001$

$R = \frac{1}{53.0} \times 1 = 0.0001$

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$R = \frac{1}{57.0} \times 1 = 0.0001$

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$R = \frac{1}{57.6} \times 1 = 0.0001$

$R = \frac{1}{57.8} \times 1 = 0.0001$

$R = \frac{1}{58.0} \times 1 = 0.0001$

$R = \frac{1}{58.2} \times 1 = 0.0001$

$R = \frac{1}{58.4} \times 1 = 0.0001$

$R = \frac{1}{58.6} \times 1 = 0.0001$

$R = \frac{1}{58.8} \times 1 = 0.0001$

$R = \frac{1}{59.0} \times 1 = 0.0001$

$R = \frac{1}{59.2} \times 1 = 0.0001$

$R = \frac{1}{59.4} \times 1 = 0.0001$

$R = \frac{1}{59.6} \times 1 = 0.0001$

$R = \frac{1}{59.8} \times 1 = 0.0001$

$R = \frac{1}{60.0} \times 1 = 0.0001$

$R = \frac{1}{60.2} \times 1 = 0.0001$

$R = \frac{1}{60.4} \times 1 = 0.0001$

$R = \frac{1}{60.6} \times 1 = 0.0001$

$R = \frac{1}{60.8} \times 1 = 0.0001$

$R = \frac{1}{61.0} \times 1 = 0.0001$

$R = \frac{1}{61.2} \times 1 = 0.0001$

$R = \frac{1}{61.4} \times 1 = 0.0001$

$R = \frac{1}{61.6} \times 1 = 0.0001$

$R = \frac{1}{61.8} \times 1 = 0.0001$

$R = \frac{1}{62.0} \times 1 = 0.0001$

$R = \frac{1}{62.2} \times 1 = 0.0001$

$R = \frac{1}{62.4} \times 1 = 0.0001$

$R = \frac{1}{62.6} \times 1 = 0.0001$

$R = \frac{1}{62.8} \times 1 = 0.0001$

$R = \frac{1}{63.0} \times 1 = 0.0001$

$R = \frac{1}{63.2} \times 1 = 0.0001$

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$R = \frac{1}{64.4} \times 1 = 0.0001$

$R = \frac{1}{64.6} \times 1 = 0.0001$

$R = \frac{1}{64.8} \times 1 = 0.0001$

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$R = \frac{1}{65.2} \times 1 = 0.0001$

$R = \frac{1}{65.4} \times 1 = 0.0001$

$R = \frac{1}{65.6} \times 1 = 0.0001$





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Niagara Falls, NY 14305-2413  
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Fax: 716-278-3902  
e-mail: [agrande@unifrax.com](mailto:agrande@unifrax.com)  
web site: [www.unifrax.com](http://www.unifrax.com)

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FAX TRANSMISSION COVER SHEET

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**Date:** January 18, 1999  
**To:** Mr. Gerry McPhee  
**Fax:** 613-990-2917  
**Co/Div:** Transport Canada  
**Re:** Rail Tank Cars  
**Sender:** Angelo Grande, Sr. Application Engineer

---

YOU SHOULD RECEIVE 4 PAGE(S), INCLUDING THIS COVER SHEET. IF YOU DO  
NOT RECEIVE ALL THE PAGES, PLEASE CALL:  
716-278-3959

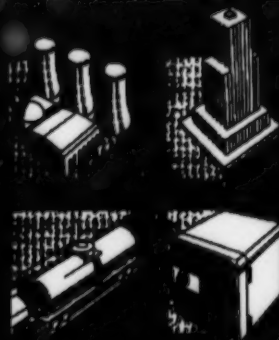
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Per our telephone conversation, enclosed please find the information you requested. I took the liberty to enlarge the thermal conductivity chart so it would legible.

Should you require additional assistance, please feel free to contact me at the above numbers and addresses. Thank you for your inquiry.



# Fiberfrax Ceramic Fiber for Fire Protection



**Unifrax Corporation**  
**Passive Fire Protection Systems**  
**Fiberfrax® DOT Approved Thermal Insulation Systems**

**DOT PROGRAM****SYSTEM DESCRIPTION**

HM-144	Fiberfrax® Tank Car Insulation, .65", min. 4.5pcf density. Encased in an 11 gauge steel jacket.
HM-144	Fiberfrax® Tank Car Insulation, .5", min. 4.5pcf density. Encased in an 11 gauge steel jacket.
HM-175	Fiberfrax® Tank Car Insulation, .5", min. 4.5pcf density. Combined with froth-in-place urethane foam. Encased in an 11 gauge steel jacket. Total thickness of insulation and foam to be no less than 2".
HM-175	Fiberfrax® Tank Car Insulation, .5", min. 4.3 pcf density Combined with 4" fiberglass (compressed to 3.5"). Encased in an 11 gauge steel jacket.
HM-175	Fiberfrax® Tank Car Insulation, 1.0", min. 4.5pcf density Combined with froth-in-place urethane foam. Encased in an 11 gauge steel jacket. Total thickness of insulation and foam to be no less than 2".
Chlorine Cars	Fiberfrax® Tank Car Insulation, 2.0", min. 4.5pcf density Combined with 2" thick fiberglass insulation. Encased in an 11 gauge steel jacket. System testing by Assoc. of American Railroads.





## FIBERFRAX®

### TANK CAR INSULATION

#### PRODUCT SPECIFICATIONS

Fiberfrax® Tank Car Insulation is a light weight, flexible needled blanket made from spun Fiberfrax ceramic fibers. Tank Car Insulation is used as fire protection insulation on railroad tank cars carrying D.O.T. regulated flammable and combustible liquids. Extra long fibers in the blanket make it the strongest one in the Fiberfrax product line. Tank Car Insulation is completely inorganic.

Tank Car Insulation is a high strength, efficient insulator with low heat storage capacity. It is unaffected by most chemicals except hydrofluoric and phosphoric acids and concentrated alkalis. If wet by water or steam, thermal and physical properties remain unaffected after drying.

Composition: ceramic fiber  
 $\text{Al}_2\text{O}_3 \geq 37\%$   
 $\text{SiO}_2 = \text{balance}$

Length: 32'

Width: 48"

Color: white

Density: 4.5 lb/ft<sup>3</sup>

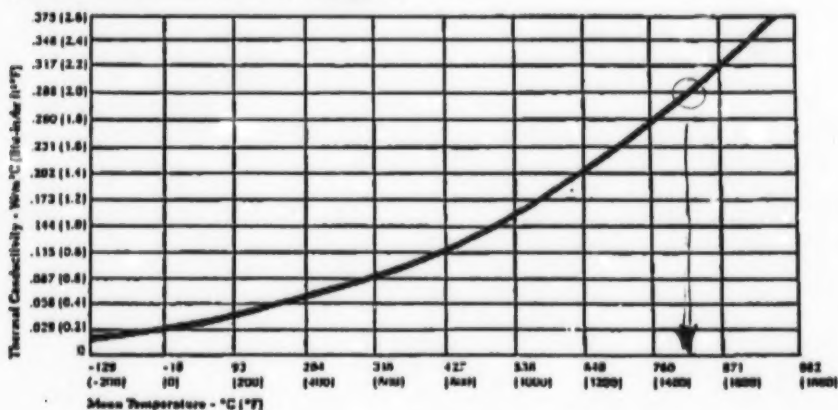
Melting Pt.: 3200°F

Thickness: .5", .65", 1", 1.5", 2"

Spec Heat: .27 Btu/lb°F

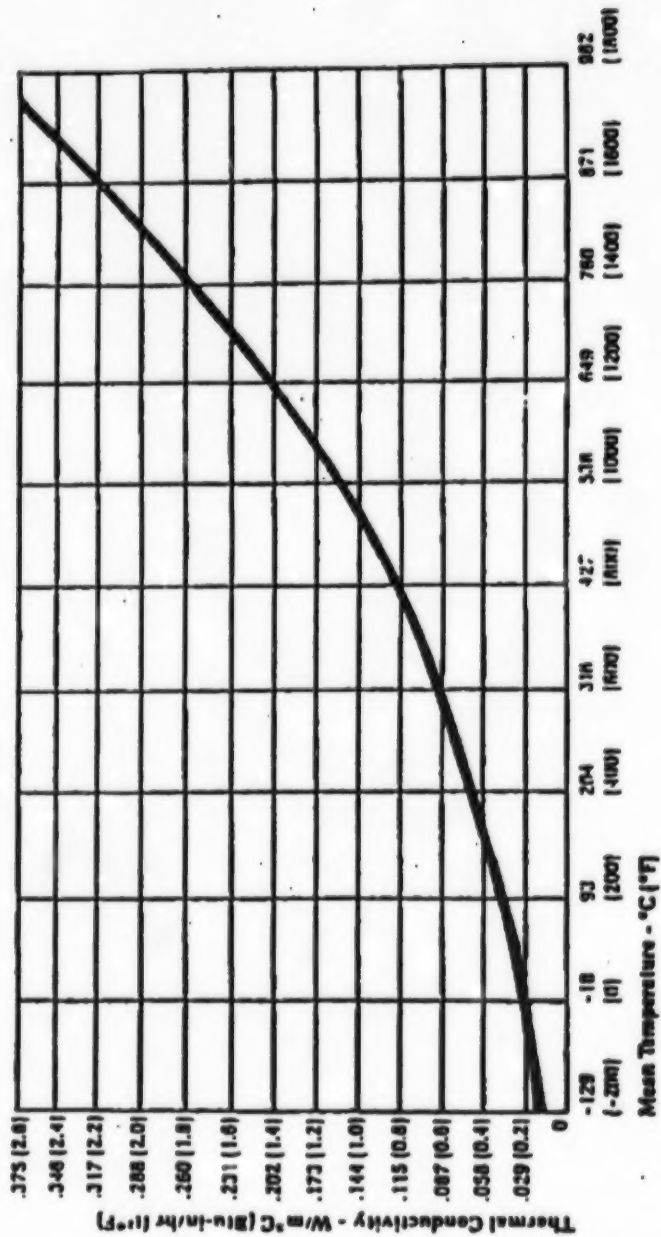
Spec. Gravity: 2.73 g/cm<sup>3</sup>

Thermal Conductivity vs Mean Temperature (per ASTM C-177)\*\*



$$4.5 \text{ lb/ft}^3 = 72.2 \text{ kg/m}^3$$

Thermal Conductivity vs Mean Temperature (per ASTM C-177)\*\*



## **Appendix G: Overall Thermal Conductance Model**

area = 1

ljacket = 3/1000

lwall = 17.5/1000

lgap = 13/1000

kwall = 45

kAIR = conductivity(AIR,t=20)

insulcond = 22.7

kinsul = insulcond \* lgap

sig = 5.67e-8

emm = .9

hann = 5

houtside = 50

hinside = 5000

q = houtside\*(t1-t2) + sig\*emm\*(t1^4-t2^4)

q = kwall/ljacket\*(t2-t3)

q = hann\*(t3-t4) + sig\*(t3^4-t4^4)/(2/emm-1)

q = kwall/lwall\*(t4-t5)

q = hinside\*(t5-t6)

{delt = 1}

t6 = 20 + 273

t1 = delt + t6

Udefect = q/delt

twall = t4

tjacket = t3

grad = sig\*(tjacket^4-twall^4)/(1/emm + 1/emm - 1)

hrad = grad/(t3-t4)

U<sub>system</sub>\*area = 1/(1/houtside/area + lgap/kinsul/area + (lwall+ljacket)/kwall/area + 1/hinside/area)

U<sub>defectradonly</sub>\*area = 1/( 1/houtside/area+ 1/hrad/area + (lwall+ljacket)/kwall/area + 1/hinside/area)

U<sub>contact</sub> = 1/(1/houtside + (lwall+ljacket)/kwall + 1/hinside)

Parametric	delt	Udefect	Udefectradonly	Insulcond	Ucontact	Ussystem
Run 1	1	4.944	2.414	0.426	4.984	0.3925
Run 2	5	4.996	2.427	0.426	4.984	0.3925
Run 3	10	5.061	2.443	0.426	4.984	0.3925
Run 4	100	6.503	2.775	0.426	4.984	0.3925
Run 5	200	8.784	3.178	0.426	4.984	0.3925
Run 6	300	11.92	3.558	0.426	4.984	0.3925
Run 7	400	16.05	3.876	0.426	4.984	0.3925
Run 8	500	21.31	4.126	0.426	4.984	0.3925
Run 9	600	27.85	4.315	0.426	4.984	0.3925
Run 10	800	45.31	4.567	0.426	4.984	0.3925

$h=5$   
outside



Parametric	delt	Udefect	Udefectradonly	insulcond	Ucontact	Ussystem
Run 1	1	8.197	4.274	0.426	48.41	0.4223
Run 2	5	8.261	4.343	0.426	48.41	0.4223
Run 3	10	8.341	4.43	0.426	48.41	0.4223
Run 4	100	10.04	6.185	0.426	48.41	0.4223
Run 5	200	12.55	8.526	0.426	48.41	0.4223
Run 6	300	15.82	11.21	0.426	48.41	0.4223
Run 7	400	20.03	14.15	0.426	48.41	0.4223
Run 8	500	25.31	17.25	0.426	48.41	0.4223
Run 9	600	31.84	20.38	0.426	48.41	0.4223
Run 10	800	49.21	26.35	0.426	48.41	0.4223

*h=50  
outside*

Parametric	delt	Udefect	Udefectradonly	insulcond	Ucontact	Ussystem
Run 1	1	4.944	2.414	22.7	4.984	4.086
Run 2	5	4.996	2.427	22.7	4.984	4.086
Run 3	10	5.061	2.443	22.7	4.984	4.086
Run 4	100	6.503	2.775	22.7	4.984	4.086
Run 5	200	8.784	3.178	22.7	4.984	4.086
Run 6	300	11.92	3.558	22.7	4.984	4.086
Run 7	400	16.05	3.876	22.7	4.984	4.086
Run 8	500	21.31	4.126	22.7	4.984	4.086
Run 9	600	27.85	4.315	22.7	4.984	4.086
Run 10	800	45.31	4.567	22.7	4.984	4.086

$h = 5$   
outside

Parametric	delt	Udefect	Udefectradonly	Insulcond	Ucontact	Ussystem
Run 1	1	8.197	4.274	22.7	48.41	15.45
Run 2	5	8.261	4.343	22.7	48.41	15.45
Run 3	10	8.341	4.43	22.7	48.41	15.45
Run 4	100	10.04	6.185	22.7	48.41	15.45
Run 5	200	12.55	8.526	22.7	48.41	15.45
Run 6	300	15.82	11.21	22.7	48.41	15.45
Run 7	400	20.03	14.15	22.7	48.41	15.45
Run 8	500	25.31	17.25	22.7	48.41	15.45
Run 9	600	31.84	20.38	22.7	48.41	15.45
Run 10	800	49.21	26.35	22.7	48.41	15.45

$h = 50.$   
outside

## **Appendix H: Local Heat Transfer and Stress Analysis**

## **Appendix**

### **Finite Element Analysis of a Tank Shell with a Hot Spot**

## 1 Introduction

To analyse a tank car in a fire, the AFTTAC model assumes that the principal stress in the tank wall is equal to the nominal hoop stress of a long cylinder with a thickness equal to the initial thickness of the tank wall. This assumption will be valid for a tank car of constant wall thickness with a uniform temperature over the entire tank shell. For the case of a tank-car with a local hot spot on the tank shell, the actual stress in the vicinity of the hot spot may be different from the nominal hoop stress. If the actual stress in the tank shell is greater than the nominal hoop stress, the AFTTAC assumptions will underestimate the time to failure, and if the stress is lower than the hoop stress the AFTTAC time to failure will be conservative.

The magnitude and distribution of stress in the hot spot will be affected by:

- i) local deformation in the vicinity of the hot spot
- ii) thinning of the material
- iii) thermal stress
- iv) changes in material properties in the hot spot due to temperature
- v) stress redistribution resulting in the hoop stress not being the principal stress

The objective of the analysis outlined in this appendix is to verify the AFTTAC assumption that the stress in a shell containing a hot spot is equal to the nominal hoop stress. A finite element model of a tank shell with a hot spot has been developed using commercial finite element software. The model is three-dimensional and accounts for the non-linear behaviour of the tank shell at elevated temperatures. Results are presented for a range of shell temperatures and hot spot sizes.

## 2 Finite Element Analysis

To solve the stress state in the vessel, a commercial finite element package has been used. In a finite element (FE) analysis the geometry being modelled is divided into a number of discrete elements. The loading condition of the geometry is modelled by applying suitable force and displacement boundary conditions. The stress and deflection of the material are then solved over the entire geometry. As in any computer simulation, the accuracy of the results depends on how the geometry and boundary conditions are modeled, the accuracy of the material properties, and the validity of the assumptions.

### 2.1 Approach

The stress in a tank shell below an insulation deficiency will depend largely on the temperature of the shell since the material properties of steel are a strong function of temperature above approximately 500°C. Even though the pressure in the tank may be constant, the stress state in the wall may change as the wall heats up due to the temperature dependence of the material properties. As the temperature of the wall increases the yield stress of the material decreases and at some point the yield stress will fall below the stress in the vessel and plastic deformation will take place. The vessel may then reach a new equilibrium stress condition or, if the temperature is high enough, continue to plastically deform until rupture.

Once the steel has reached a critical temperature, the thinning of the material leading to failure occurs very rapidly. Therefore, within the 30 and 100 minute time periods considered in qualification of tank-cars, the time to failure can be assumed to be



more dependent on the heat transfer to the tank shell than the time dependent strain of the steel at elevated temperatures. With this assumption, the stress in the tank shell up to the point of rapid thinning, can be approximated using a steady state analysis. This type of analysis determines the stress in the shell when the material is in equilibrium under constant temperature and pressure. The use of a steady state analysis will give an estimate of the stress in the hot spot without requiring a computationally intensive time dependent creep analysis. A steady state analysis is therefore the method of approach used here. In some instances this analysis may not predict failure when in reality the additional effects of creep are important.

## **2.2 Finite Element Software**

All simulations were completed using ANSYS 5.3. This is a commercial finite element package capable of non-linear plastic analysis.

## **2.3 FE Model**

### **2.3.1 Assumptions**

The following assumptions are made in developing the model for the FE analysis:

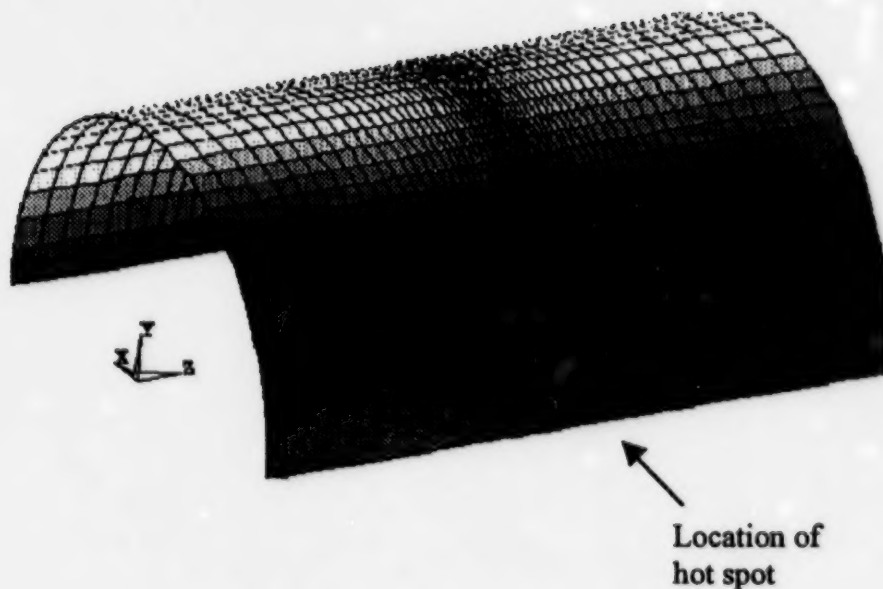
- i) Temperature of hot spot and vessel remains constant.
- ii) Pressure in vessel remains constant.
- iii) Effects of creep are small.
- iv) All defects are located away from the elliptical ends.
- v) All defects are isolated from other defects.

### **2.3.2 Model Geometry**

The geometry used in the analysis, shown in Figure 1, was developed to decrease complexity and computation time while retaining the main stress characteristics of a tank car. To increase the speed of the FE analysis, the computational domain was reduced by taking advantage of symmetry in the tank car model. Circumferential symmetry required only one half of the tank (a 180° sector) be modelled. Axial symmetry was not used as it was found to produce inconsistent results.

The elliptical ends were not modelled in order to reduce the computational domain and simplify mesh generation. The end caps were simulated by applying appropriate boundary conditions: a uniform distributed load over the ends of the cylindrical section to replace the axial stress in the vessel wall; and zero radial displacement and rotation boundary condition on the vessel ends to simulate the end caps restricting the movement of the cylinder.

The length of the domain was also reduced since the relative size of the deficiencies was small compared to the size of the tank. Successive trials were conducted and it was found that for hot spots 1.0 m wide the results were independent of length down to a ¼ length scale model (4 m).



**Figure 1: model geometry**

### 2.3.3 Elements

Elements with a thickness equal to that of the tank car shell were used resulting in only one element through the thickness of the tank car wall (shell elements). This was possible because of the small ratio of tank wall thickness to diameter. In all cases ANSYS SHELL43 plastic large strain shell elements were used. The major properties of these elements are:

- Large deflection
- Large strain
- Plasticity
- 4 nodes with 6 degrees of freedom at each node
- variable thickness

### 2.3.4 Grid

The grid used for all simulations is shown in Figure 1. The grid consisted of square shell elements with a linear change in element width along the length and around the circumference of the model. This increased the density of the grid in the vicinity of the defect giving about 30 elements across the defect width. Grid sensitivity studies showed that the solution was grid independent for this grid density.

### 2.3.5 Wall Temperatures

The wall temperature distribution applied in the defect was calculated using a two-dimensional heat transfer model of a defect in an insulated tank car wall (see Appendix XX). In all cases the view factor of the inner wall to the lading was 0.5 and the fire temperature was adjusted until the peak temperature in the centre of the defect was equal to 400, 500, 600, 700, or 800°C. The temperature distribution for half of a 1.0 m defect calculated using the model is shown in Figure 2. Far from the defect the shell temperature is that of an insulated wall under the same fire conditions. This temperature distribution was then superimposed on the finite element grid and the temperature of the nodes set accordingly. The same temperature gradient was applied in the axial and circumferential directions. At the corners of the defect the temperature distribution was slightly rounded to reduce stress concentrations that may be caused by artificially large temperature gradients. A sample wall temperature distribution is shown in Figure 3.

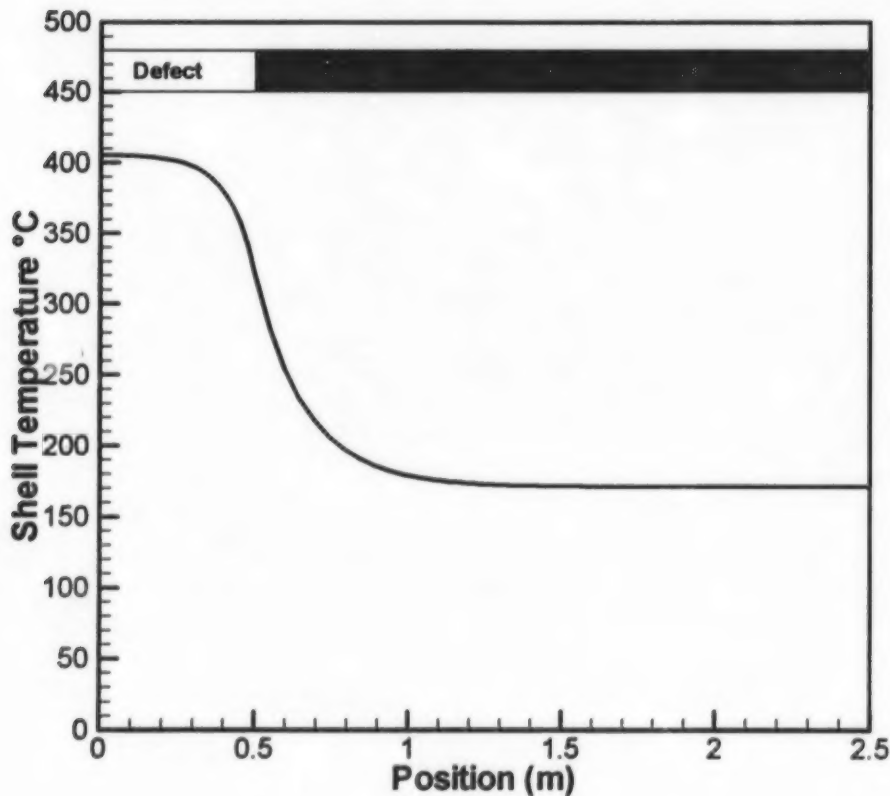


Figure 2: Applied temperature distribution 1.0 m total defect width

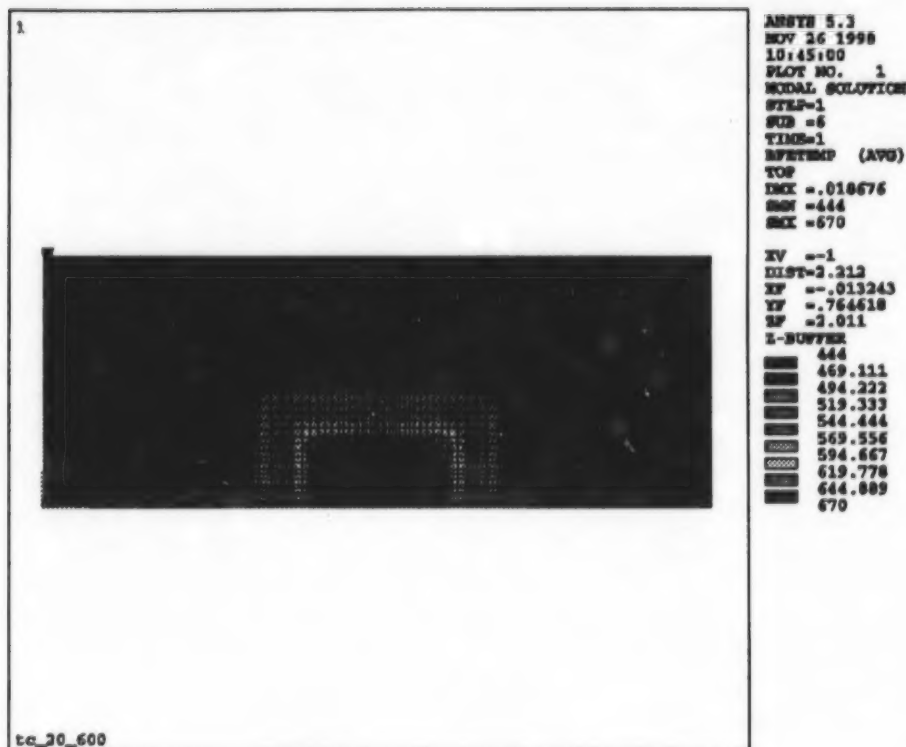


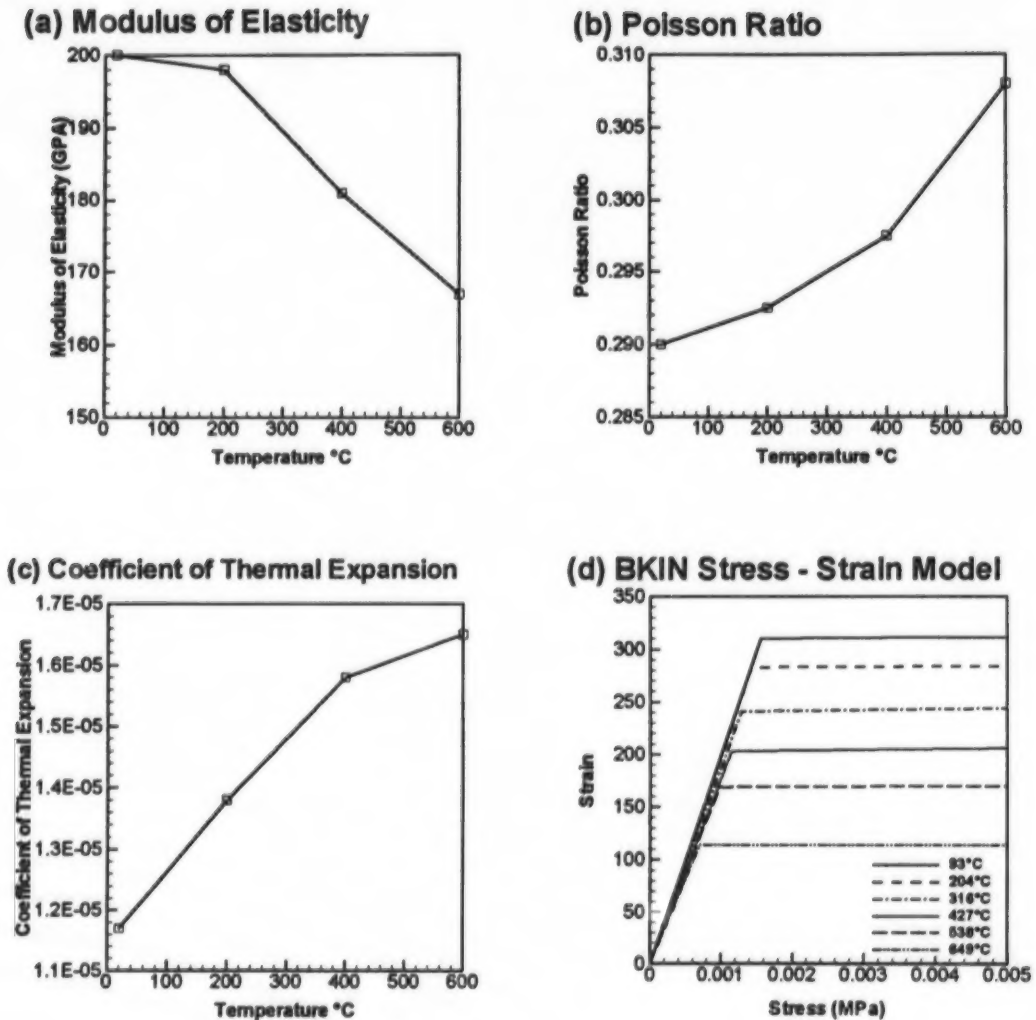
Figure 3: Temperature distribution in 1.0 m defect, temperatures units : K

### 2.3.6 Material Properties

Steel material properties vary considerably over the range of temperatures of interest in the analysis, introducing material non-linearities into the analysis. Material properties for steels at elevated temperatures are not readily available. Of the steels for which high temperature mechanical properties were found, ARMCO LO-TEMP steel (an ASTM-537 steel) was found to be the closest to those specified in section 79.100-7 of the CAN/CGSB-43.147-97 specifications.

To account for the temperature dependence of Young's modulus, Poisson ratio, and coefficient of thermal expansion, values of the properties were entered into the ANSYS database at 20°, 200°, 400°, and 600°C (see Figure 4(a)-(c)).

The changes in the yield stress with temperature and the plastic behaviour of the steel was modelled using the Bilinear Kinematic Hardening (BKIN) model included in ANSYS. This simple model was chosen because the limited material property data at elevated temperatures did not warrant a more advanced model. The BKIN model constructs the stress strain curve for the material at each temperature given the Young's modulus (slope of the elastic portion of the curve), the yield stress, and the tangent modulus (slope of the plastic portion of the curve). Stress-strain curves were input at 7 temperatures between 20°C and 650°C (Figure 4(d)).



**Figure 4: ASTM 537 (Armco LO-TEMP) temperature dependent material properties [3].**

### 2.3.7 Solution Tools

Because of the nature of the non-linear plastic problem being solved, several features of ANSYS were invoked to help improve the accuracy of the solution and to speed up convergence. A brief description of each feature used is given below:

- i) *NLGEOM – large deformation effects* : This feature accounts for the stiffness changes in elements due to the change in the shape of the elements resulting from large deflections and strains. This was included to account for the changes in the material in the hot spot where the material thins and bulges.

- ii) *Load Steps* : For non-linear applications, the load must be applied in small steps with an equilibrium solution being obtained at each load step. This allows the solution to capture the non-linearities introduced through the material properties and plastic behaviour in the vicinity of the hot spot.
- iii) *LNSRCH – Line Search* : An relaxation factor in the Newton Raphson solution technique which promotes convergence.
- iv) *PRED – Predictor* : A factor which uses the history of the solution process to improve the next guess in the numerical solution.

The accuracy of the results depends on the density of the grid and rate at which the loads are applied, the greater the grid density and the more load steps the more accurate the solution. These conditions, however, lead to a large number of computations and there is a trade off between accuracy and speed of analysis.



### 3 Results

The goal of this study was to determine how the temperature and size of a hot spot in the tank shell affects the stress state in the shell. In the simple stress approach used in the models in the body of the report, the tank will fail if the ultimate strength is exceeded at any location in the shell. In a hot spot the point of greatest importance will therefore be the centre of the hot spot where the temperature is greatest. Results of the stress state in the centre of the defect will be given along with some detailed results.

Simulations were run for a range of square deficiencies and shell temperatures. Table 1 summarises the conditions used in the simulations. As will be shown in the next section, converged solutions were not obtained for all cases.

Table 1: Summary of simulation conditions

Parameter	Value
Deficiency shape	Square
Deficiency widths	0.2, 0.5, 1.0 m
Shell temperature	400, 500, 600, 700, 800°C
Shell thickness	0.0175 m
Internal pressure	340 psig

#### 3.1 Summary of Results

The validity of using the nominal hoop stress can be determined by normalising the stress in the centre of the defect by that of a tank shell with no defects. The normalised stresses for the different deficiency widths and shell temperatures are shown in Figure 5. A normalised value of one indicates the stress is equal to that in a tank shell with no hot spot. Both the first principal stress and the von Mises stress are shown. It should be noted that in a pressurised cylindrical shell at a uniform temperature the principal stress is aligned with the axis of the cylinder. However, with the presence of hot spot this may not be the case.

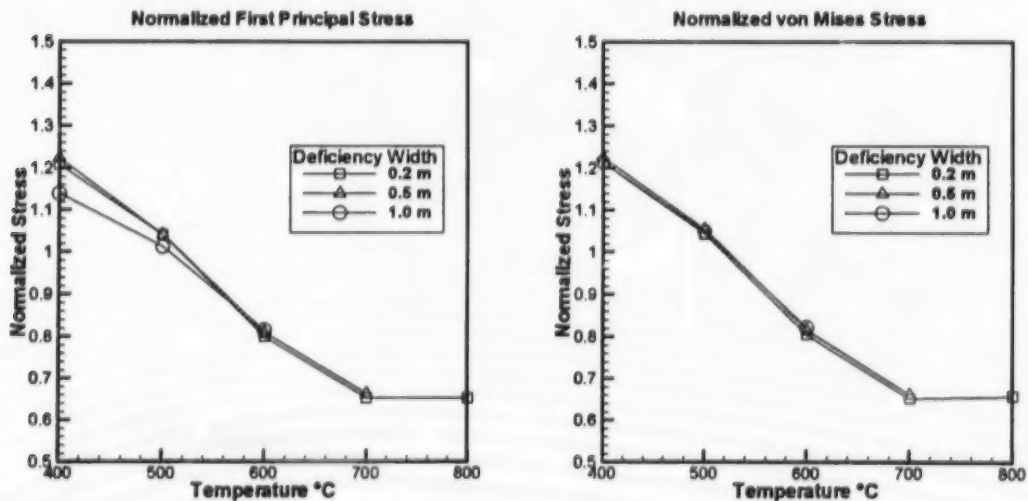


Figure 5: Normalised stress in centre of hot spot

Figure 5 shows that the stress in the defect for temperatures of up to 600°C is essentially independent of defect width for defect widths of 0.2 to 1.0 m. This suggests that the phenomena causing the changes in the hot spot are very localised and the same effect will be seen for both small and large defects. The finite element solution did not converge for a 1.0m defect at 700°C or 800°C and for a 0.5 m defect at 800°C. In these cases the shell elements became too thin during the solution. This would suggest that under the imposed temperature conditions the tank shell would rupture before equilibrium conditions were reached.

Figure 5 also indicate that at 400°C the stress in the defect is 20% greater than for no hot spot. At this temperature the combination of deformation and thermal expansion acts to actually increase the stress in the hot spot. As the temperature of the shell further increases the yield stress decreases to the point that the shell in the vicinity of the hot spot can no longer sustain the stress level. The material plastically deforms to relieve the stress until equilibrium is reached. At 500°C the stress is approximately equal to the case of no hot spot. With further increases in shell temperature the stress in the centre of the hot spot falls below that of the case of no hot spot. For shell temperatures of 700°C or greater this leads to stress levels in the centre of the hot spot 30% below the nominal hoop stress.

Detailed results for examples of both increased and decreased stress in the hot spot are given in the following sections.

### **3.2 Detailed results Case 1: increased stress in hot spot**

The results for the case of a 0.5 m defect with a peak wall temperature of 400°C are summarised in Figure 6 to Figure 12. This is an example of tank in which the peak stress in the defect is greater than that for a tank with no hot spot. In all cases the view shown in the figures is looking directly down onto the tank with the line of symmetry located along the bottom edge of the figure. The defect is located in the centre of the tank along the line of symmetry.

The change in material properties at elevated temperature results in the tank shell bulging out in the radial direction in the area of the hot spot as shown in Figure 7. This deformation, combined with the thermal expansion of the shell material, results in an axial stress distribution that is compressive at the axial edges of the defect and tensile in the centre of the defect (see Figure 9). The material beside the defect in the circumferential direction has a greater tensile axial stress than nominal since the expansion of the hot material in the hot spot puts the adjacent cool material in tension.

The same effects are not observed in the axial direction. The combination of tank deformation and thermal expansion actually leads to an increase in the hoop stress within the hot spot (see Figure 8). This is likely due to the difference in stiffness of the vessel in the axial and circumferential direction. The curvature of the tank in the circumferential direction will allow the shell to deflect more easily than in the axial direction. Therefore, as the material expands due to its increased temperature, it goes into compression in the axial direction, but because of deformation, remains in tension in the circumferential direction. The overall result is a principal stress in the hot spot greater than the nominal direction. The compression in the axial direction and tension in the circumferential direction is also shown in the plastic strain in Figure 11 and Figure 12.



```

RPTTEMP (AVG)
TOP
DMX =.014672
DMN =.445
SMX =.670

IV =-1
DIST=2.211
XF =-.009088
YF =.764754
ZF =2.01
Z-BUFFER
0.445
0.470
0.495
0.520
0.545
0.570
0.595
0.620
0.645
0.670

```

Figure 6: Shell temperature distribution, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$



```

UX
TOP
RSYS=1
DMX =.014672
DMN =-.013846

IV =-1
DIST=2.211
XF =-.009088
YF =.764754
ZF =2.01
Z-BUFFER
0
0.001538
0.003077
0.004615
0.006154
0.007692
0.00923
0.010769
0.012307
0.013846

```

Figure 7: Radial deformation, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$



```

SY (AVG)
TOP
RSYS=1
DMX =.014672
DMN =-.324E+09
SMX =.263E+09

IV =-1
DIST=2.211
XF =-.009088
YF =.764754
ZF =2.01
Z-BUFFER
-.324E+09
-.259E+09
-.193E+09
-.128E+09
-.628E+08
.245E+07
.677E+08
.133E+09
.198E+09
.263E+09

```

Figure 8: Hoop stress, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$



Figure 9: Axial stress, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$

S1 (AVG)  
 TOP  
 RSYS=-1  
 DMX = .014672  
 SMX = -.208E+09  
 SMI = .263E+09  
 XV = -1  
 DIST=2.211  
 XF = -.009088  
 YF = .764754  
 ZF = 2.01  
 E-NUMBER  
 -.208E+09  
 -.156E+09  
 -.104E+09  
 -.512E+08  
 .112E+07  
 .535E+08  
 .106E+09  
 .150E+09  
 .211E+09  
 .263E+09



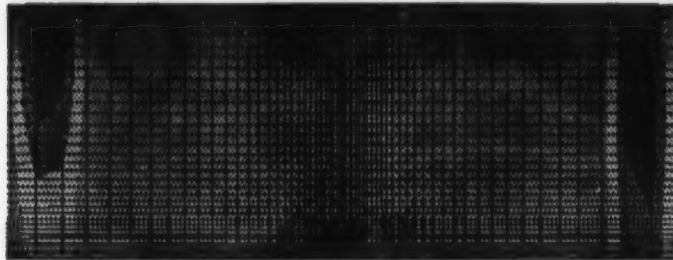
Figure 10: Principal stress, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$

S1 (AVG)  
 TOP  
 RSYS=-1  
 DMX = .014672  
 SMX = .225E+07  
 SMI = .276E+09  
 XV = -1  
 DIST=2.211  
 XF = -.009088  
 YF = .764754  
 ZF = 2.01  
 E-NUMBER  
 .225E+07  
 .327E+08  
 .631E+08  
 .935E+08  
 .124E+09  
 .154E+09  
 .185E+09  
 .215E+09  
 .246E+09  
 .276E+09



Figure 11: Plastic hoop strain, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$

EPLY (AVG)  
 TOP  
 RSYS=-1  
 DMX = .014672  
 SMX = -.372E-03  
 SMI = .001798  
 XV = -1  
 DIST=2.211  
 XF = -.009088  
 YF = .764754  
 ZF = 2.01  
 E-NUMBER  
 -.372E-03  
 -.131E-03  
 .110E-03  
 .351E-03  
 .592E-03  
 .834E-03  
 .001075  
 .001316  
 .001557  
 .001798



```

APPLE (AVG)
TOP
EYES-1
DKE -.014679
DKE -.420E-03
DKE -.268E-03

XV =-1
DIST-2.211
XF =-.009088
YF =.764754
ZF =2.01
I-SURF
      -.420E-03
      -.350E-03
      -.273E-03
      -.196E-03
      -.118E-03
      -.409E-04
      .364E-04
      .114E-03
      .191E-03
      .268E-03

```

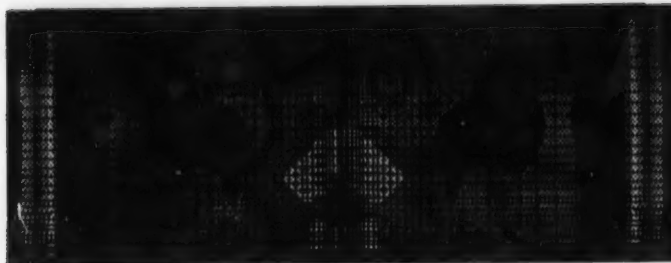
Figure 12: Plastic axial strain, 0.5 m defect,  $T_{max}=400^{\circ}\text{C}$

### 3.3 Detailed results Case 2: decreased stress in hot spot

The stress state for a 0.5 m defect with a maximum shell temperature of  $700^{\circ}\text{C}$  are summarised in Figure 13 to Figure 17. These results are representative of the case of decreased stress in the hot spot.

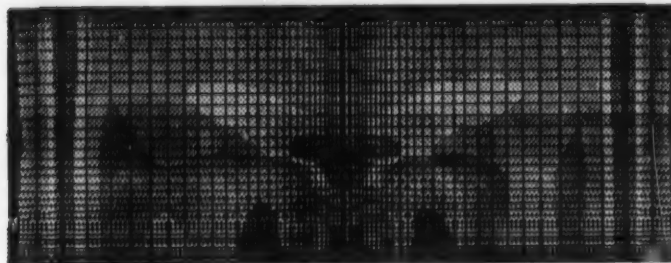
As the shell temperature increases the strength of the steel continues to decrease. To achieve equilibrium the steel plastically deforms to locally relieve the stress, transferring the load to the adjacent material. This stress relief is visible in the plot of hoop stress (Figure 14) which shows a reduction in stress in the hot spot and increase in material to the sides of the defect. Figure 14 shows a similar pattern for axial stress as in the low temperature case, compression at the axial ends of the defect, slight reduction in tensile stress in the defect, and tension on the circumferential side of the defect. The reduction in both the hoop and axial stress within the hot spot combine to give a principal stress that is lower in the defect than the nominal stress as shown in Figure 15. Comparing the plastic strain for case 1 (Figure 11 and Figure 12) to that of case 2 (Figure 16 and Figure 17) it can be seen that the pattern of strain is similar, but covers a larger area and has a larger magnitude for the higher temperature case.





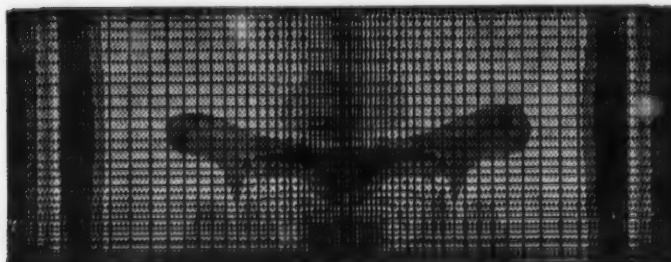
8Y (AVG)  
 TOP  
 RSYB=1  
 IMX =-.037036  
 SMY =-.281E+09  
 SMX =.268E+09  
 IV =-1  
 DIST=2.217  
 XF =-.02912  
 YF =.767057  
 ZF =2.016  
 Z-BUFFER  
 .281E+09  
 .220E+09  
 .159E+09  
 .984E+08  
 .374E+08  
 .236E+08  
 .846E+08  
 .146E+09  
 .207E+09  
 .268E+09

Figure 13: Hoop stress, 0.5 m defect,  $T_{max}=700^{\circ}\text{C}$



8Z (AVG)  
 TOP  
 RSYB=1  
 IMX =-.037036  
 SMY =-.154E+09  
 SMX =.265E+09  
 IV =-1  
 DIST=2.217  
 XF =-.02912  
 YF =.767057  
 ZF =2.016  
 Z-BUFFER  
 .154E+09  
 .108E+09  
 .610E+08  
 .143E+08  
 .323E+08  
 .789E+08  
 .125E+09  
 .172E+09  
 .219E+09  
 .265E+09

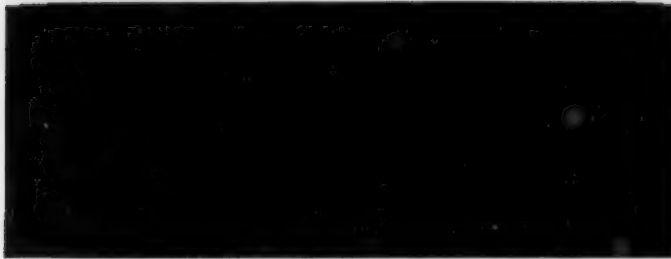
Figure 14: Axial stress, 0.5 m defect,  $T_{max}=700^{\circ}\text{C}$



81 (AVG)  
 TOP  
 IMX =-.037036  
 SMY =.261E+07  
 SMX =.276E+09  
 IV =-1  
 DIST=2.217  
 XF =-.02912  
 YF =.767057  
 ZF =2.016  
 Z-BUFFER  
 .261E+07  
 .330E+08  
 .633E+08  
 .937E+08  
 .124E+09  
 .154E+09  
 .185E+09  
 .215E+09  
 .245E+09  
 .276E+09

Figure 15: Principal stress, 0.5 m defect,  $T_{max}=700^{\circ}\text{C}$





```

HPLY (AVG)
TOP
RSTN=1
DMX =.037036
SMN =-.001000
SMX =.041122

IV =-1
DIST=2.217
XF =-.02912
YP =.767057
ZF =2.016
E-SOFFER
      -.001000
      -.002962
      -.007732
      -.012502
      -.017272
      -.022042
      -.026812
      -.031582
      -.036352
      -.041122

```

Figure 16: Hoop strain, 0.5 m defect, Tmax=700°C



```

HPLY (AVG)
TOP
RSTN=1
DMX =.037036
SMN =-.003429
SMX =.034E-03

IV =-1
DIST=2.217
XF =-.02912
YP =.767057
ZF =2.016
E-SOFFER
      -.003429
      -.002956
      -.002482
      -.002008
      -.001535
      -.001061
      -.000587E-03
      -.000114E-03
      -.000360E-03
      -.000834E-03

```

Figure 17: Axial strain, 0.5 m defect, Tmax=700°C

### 3.4 Limitations of the Analysis

In developing the stress model, several assumptions were made to simplify the analysis and reduce the computational effort required to obtain a solution. In some cases these assumptions limit the validity of the results. The major limitations of the analysis are summarised here.

1. *Steady state* : the actual deformation of the tank will be a time dependent event. By assuming steady state the key effects of time dependent wall temperatures and time dependent material properties i.e. creep, are not captured in the analysis. This obviously prevents time to failure from being calculated. However, as the heat transfer is a relatively slow process and the final stages of creep are very rapid, the steady state analysis will capture the relative effects of wall temperature and defect size, if not the exact values.
2. *Single isolated defect* : The analysis only looked at single defects away from the ends of the tank. The present results will not be valid for deficiencies adjacent to the elliptical ends of the tank or in close proximity with other defects.
3. *Material properties*: The model that was used for material strength does not allow for an ultimate strength, simply a yield strength with a slope of the stress-strain curve in

the plastic region. This does not allow for the prediction of vessel rupture and probably led to non-convergence in cases where the vessel ruptured i.e. 1.0 m defect at 800°C.

4. *Defect shape*: Only square defects were tested. It is expected that the aspect ratio of the defect would affect the results. For example a defect longer in the circumferential direction would be more dependent on changes in the axial stress than one longer in the axial direction.
5. *Solution convergence* : The applied boundary conditions were symmetric on the tank but in some solutions, e.g. Figure 10, the solution is not symmetrical on the tank. This suggests that the solution may not have reached complete convergence. The convergence criterion used were tight and any discrepancies are thought to be small.

It should be noted that the current analysis is a very limited study of the stress in a hot spot in a tank car wall. It should only be used to establish general trends for the effect of hot spot temperature and size on the stress on the tank shell. A more detailed study using more advanced material models and validation is required to establish more accurate results.

#### **4 Conclusions**

A limited analysis of the stress state in a tank car shell with a hot spot has been examined using commercial finite element software. The following conclusions can be made from this analysis.

1. The state of stress is independent of the size of square defects for the range of 0.2-1.0 m defect widths.
2. The peak shell temperature strongly effects the stress in a hot spot. For a peak shell temperature of 400°C the stress in the hot spot was approximately 20% greater than for the non-defect case. Conversely at maximum shell temperature of 800°C the stress in the hot spot is 30% less than the non-defect case.
3. Solutions did not converge for 0.5 m defects at 800°C and 1.0 m defects at 700°C and 800°C. This suggests that the tank would rupture under these conditions.

## **5 References**

1. Ansys 5.3 on-line manuals.
2. "Construction and Maintenance of Tank Car Tanks and Selection and Use of Tank Car tanks, Portable Tanks and tail Cars for the Transportation of Dangerous Goods by Rail", CAN/CGSB-43.147-97.
3. Structural Alloys Handbook, vol 3, 1996 edition, Purdue University, West Lafayette, IN.

## **Appendix**

### **2-D Effects on the Heat Transfer in Tank Car Insulation Deficiencies**

## 1 Introduction

The heat transfer models presented in the body of this report assume that the heat transfer in a tank car wall is one dimensional in a direction perpendicular to the wall. This is valid where the heat flux through the wall is much greater than that parallel to the wall, i.e. the heat transfer in the centre of large deficiencies will essentially be one dimensional. However, as the size of the deficiencies decreases the effect of conduction along the tank shell increases, generally lowering the peak temperature in the deficiency.

The results of a 2-D heat transfer model are presented in this appendix in order to illustrate under what conditions the assumption of one-dimensional heat transfer is valid. The results include wall temperatures for transient simulations over a range of fire temperatures and deficiency widths. The effect of adjacent deficiencies in close proximity with each other has also been examined using a steady state analysis.

## 2 Heat Transfer Model

The heat transfer model used in the analysis is briefly described here. Details of the model can be found in TP 13203E.

A finite difference method has been used to model the heat transfer in the steel jacket, steel shell and insulation surrounding an insulation deficiency. The model includes the heat transfer due to:

- radiation between the tank wall and the fire and lading
- convection within in the deficiency and the interior of the tank
- conduction within the steel and insulation

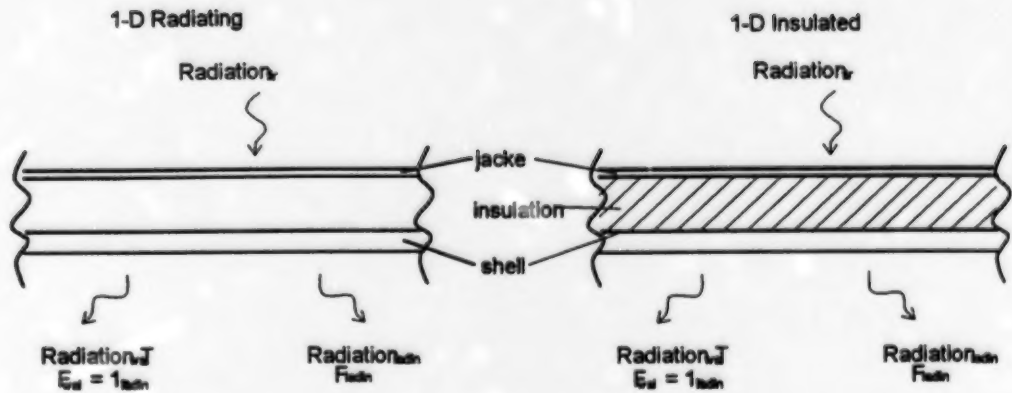
To simplify the analysis, the tank car wall has been modeled as a finite 2-D planar wall shown in Figure 1. The deficiency was assumed to be symmetrical requiring only one half of the wall to be considered in the analysis. The major assumptions which were used to formulate the model are summarized in Table 1.

**Table 1 : Model assumptions**

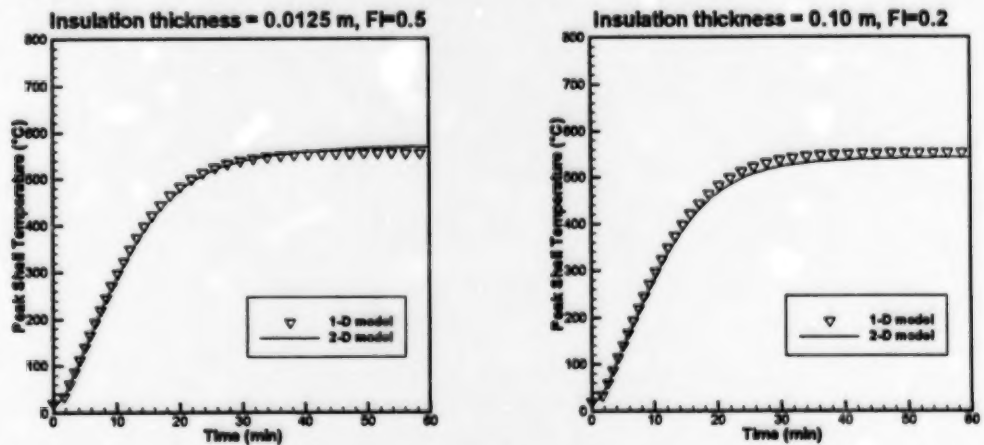
Assumption	Justification
Planar	<ul style="list-style-type: none"><li>• Tank diameter is large (3 m)</li><li>• For relatively small defects (0.5 m) curvature effects will be minimal</li></ul>
2-D	<ul style="list-style-type: none"><li>• Valid for large aspect ratio defects</li><li>• Greatly simplifies equations</li></ul>
Finite length with adiabatic end walls	<ul style="list-style-type: none"><li>• For single deficiencies length is adjusted until gradients near the end wall are small</li></ul>
Exterior heat transfer from the fire only by radiation	<ul style="list-style-type: none"><li>• <math>q_{rad} \gg q_{conv}</math></li></ul>
Convective heat transfer within the tank car to a constant temperature gas with a constant heat transfer coefficient of 5 W/m°C	<ul style="list-style-type: none"><li>• Convective heat transfer will be through natural convection</li><li>• Gas temperature will be higher near the wall, but since <math>q_{conv} \ll q_{rad}</math> the assumption of constant T will have a minimal effect</li></ul>







**Figure 2: Schematic of 1-D models used for validation**



**Figure 3: Validation results for 2-D transient model,  $T_{fire}=820^{\circ}\text{C}$**

is independent of the deficiency width and is effectively an infinite wall. For both insulation thickness' and lading view factors, the results for both models compare very favorably. The slight divergence at later times is most likely due to approximating the wall temperature for  $F_{wall}$  with the wall temperature farthest from the deficiency in the 2-D model.

Table 2 compares the equilibrium steady state shell temperatures in the centre of a 1 m deficiency for the 2-D model to the results of the 1-D model. As with the transient case, the results show good correspondence between the two models.

**Table 2 : Validation of steady state model,  $T_{fire}=816^{\circ}\text{C}$**

Insulation thickness (m)	$F_l$	$T_{shell}$ ( $^{\circ}\text{C}$ ) 1-D	$T_{shell}$ ( $^{\circ}\text{C}$ ) 1-D
0.10	.2	560.4	561
0.10	.5	557	557
0.0125	.2	552.7	551.7
0.0125	.5	552.2	551.2

### 3 Results

Transient and steady state simulations were carried out over a range of insulation thickness', deficiency widths, gap spacing, lading view factors, and fire temperatures. The geometric and heat transfer properties used in the simulation are presented in Table 3.

**Table 3 Geometric and heat transfer parameters for numerical simulations**

Parameter	Value
Insulation thickness	0.0125, 0.10 m
Insulation deficiency widths	0.01 - 1.0m
Jacket thickness	3 mm
Shell thickness	17.5 mm
Lading view factor	0.2, 0.5
View factor from jacket to fire	1
Lading temperature	333 K
Steel conductivity	30 W/m K
Insulation conductivity	0.04 W/m K
Steel emissivity	0.9
Insulation emissivity	0.3
Convective heat transfer coefficient	5 W/m <sup>2</sup> K

#### 3.1 Transient simulations

Transient simulations were run to determine how the width of the insulation deficiency affected the peak temperature in the deficiency. Additional conditions of the simulations are given in Table 4. As will be shown in the next section, 2 m width of insulated wall beside the deficiency was sufficient for the temperature of the wall in the deficiency to be independent of the width of the insulated section. A coarse grid was used for calculation to reduce the calculation time. Grid sensitivity analysis showed that the error in the temperature is approximately  $\pm 5^{\circ}\text{C}$ .

The results of the transient analysis are shown in Figure 4 to Figure 7. Only the peak average wall temperature is shown in the figures as this is the critical parameter for determining the burst pressure of a tank. The peak average wall temperature is the average temperature through the thickness of the shell in the centre of the deficiency.

**Table 4: Transient simulations**

Parameter	Value
Initial tank wall temperature	20°C
Fire temperature	800 - 900°C
Simulation time	60 minutes
Width of insulated wall beside deficiency	2 m

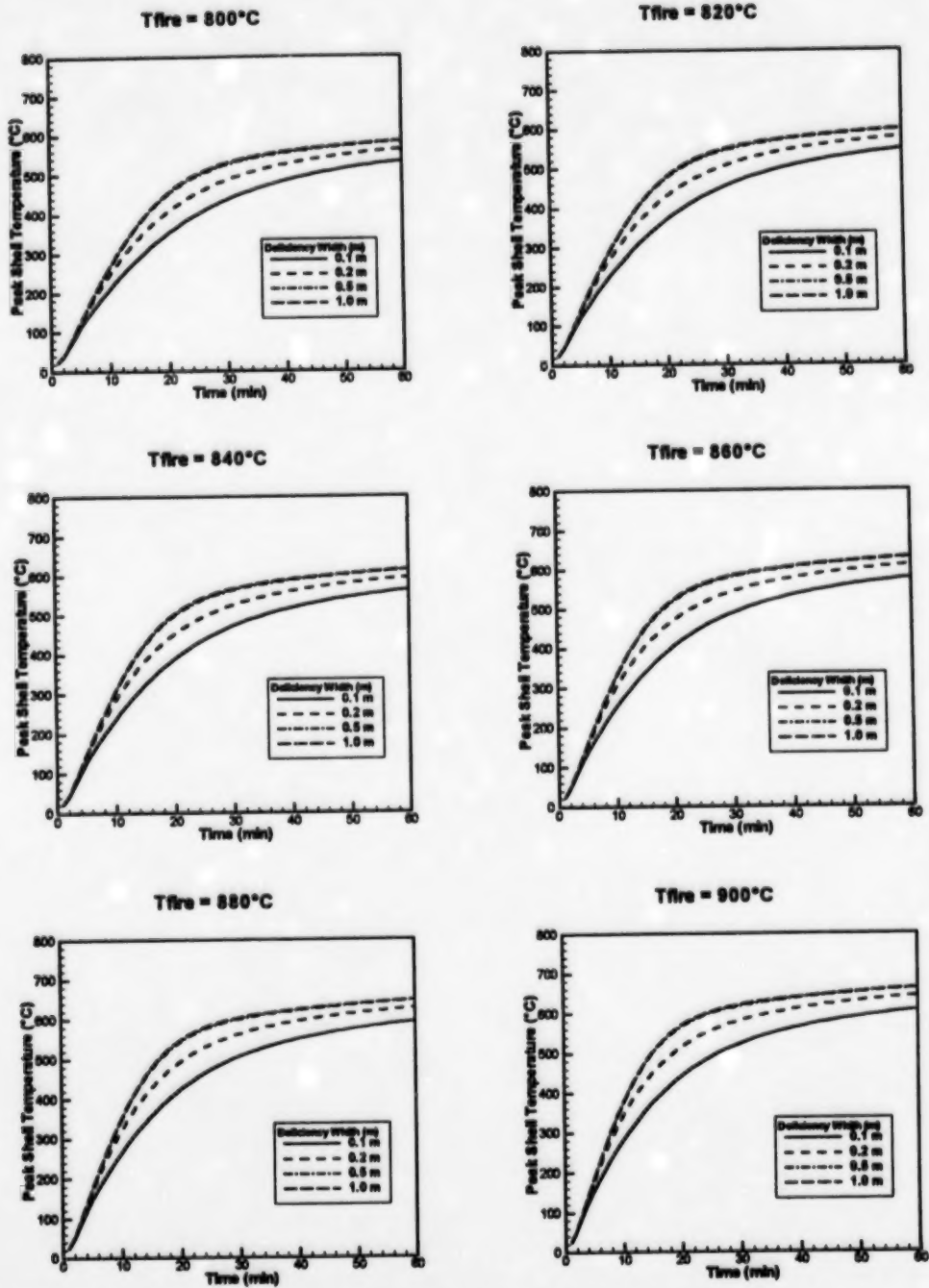
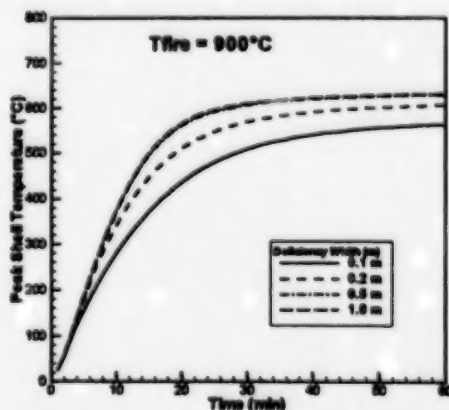
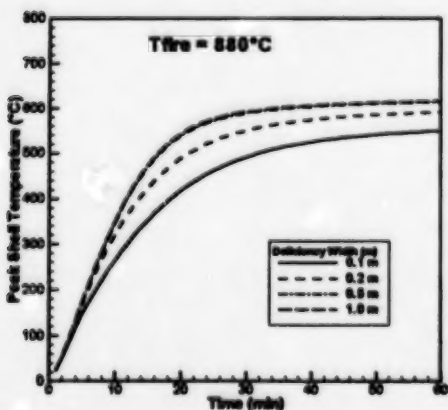
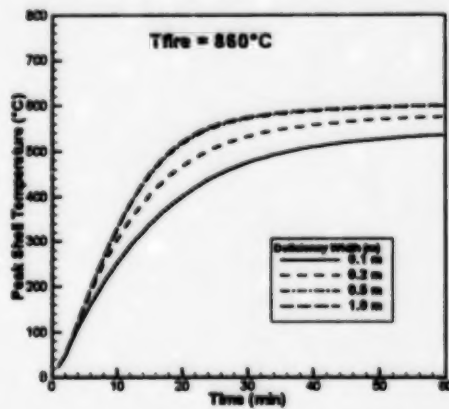
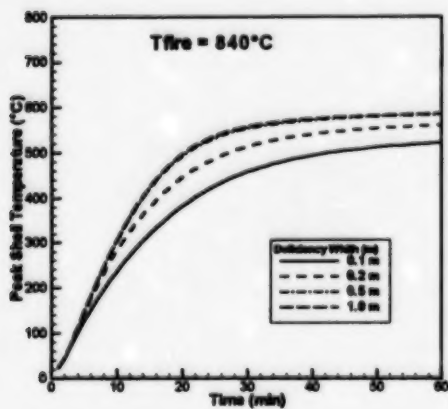
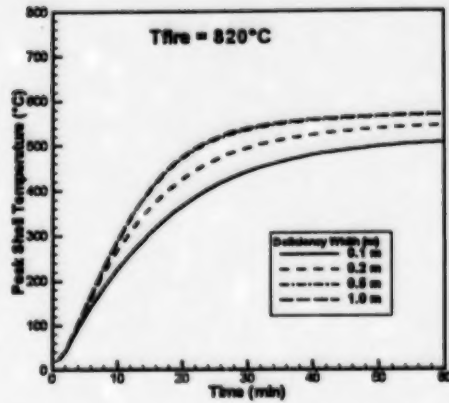
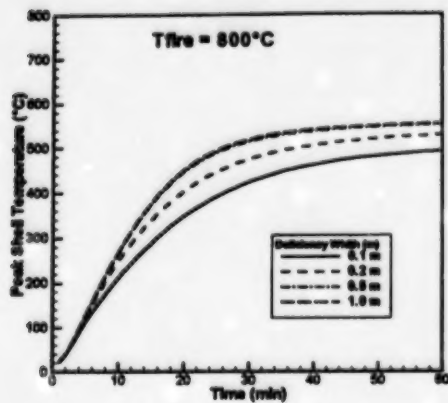


Figure 4 : Peak shell temperature, insulation thickness =13 mm,  $F_1=0.2$



**Figure 5: Peak shell temperature, insulation thickness = 13 mm,  $F_r=0.5$**

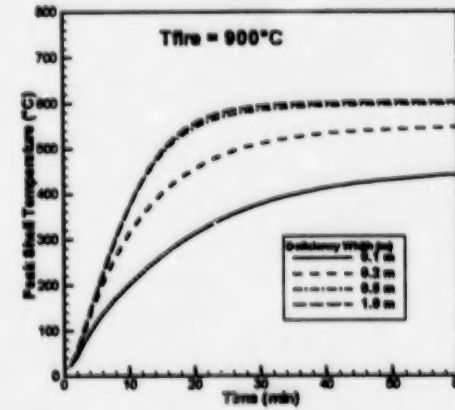
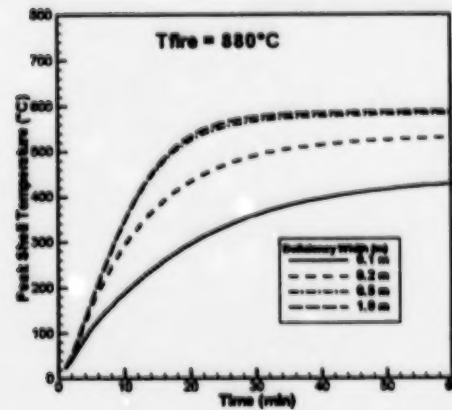
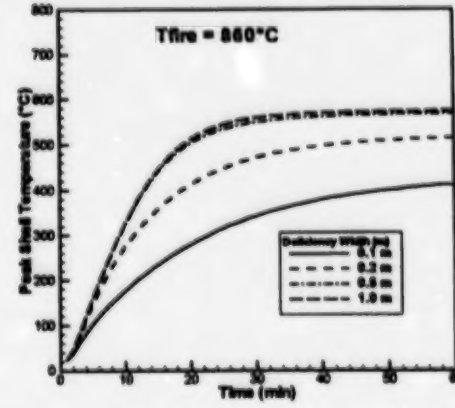
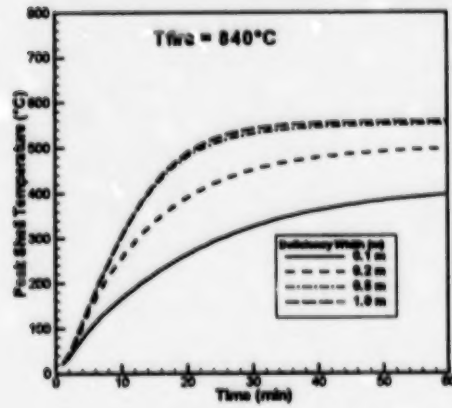
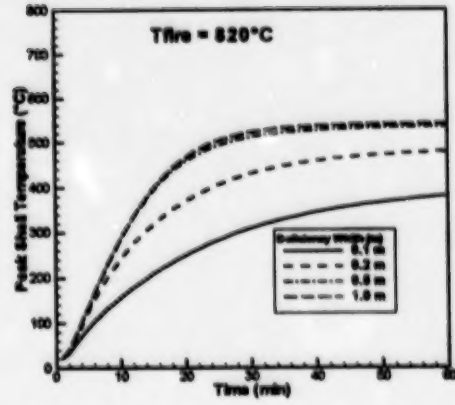
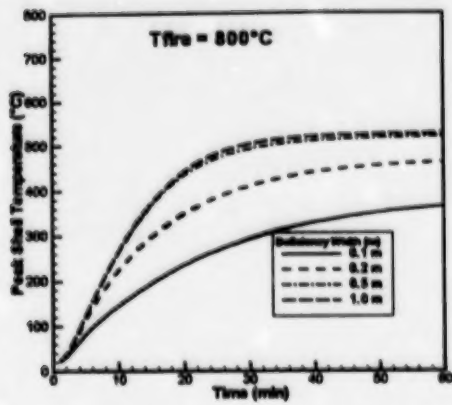
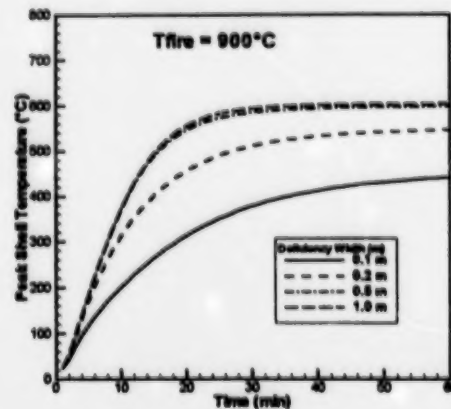
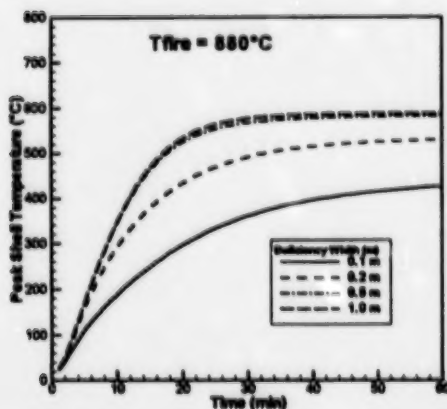
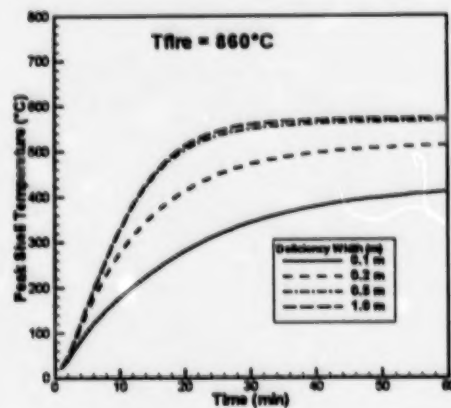
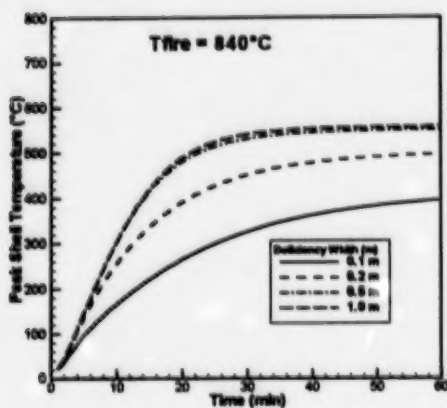
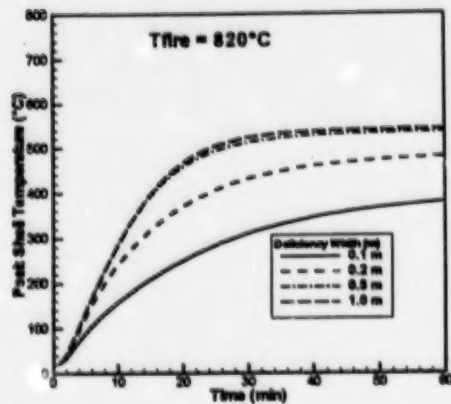
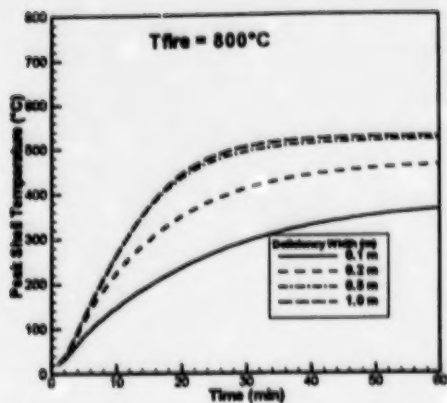


Figure 6: Peak shell temperature, insulation thickness=100 mm,  $F_i=0.2$





**Figure 7: Peak shell temperature, insulation thickness=100 mm,  $F_i=0.5$**

The results shown in Figure 4 to Figure 7 consistently show that as the deficiency width decreases below 0.5 m the peak temperature in the deficiency decreases due to conduction in the wall. At 60 minutes the difference in the peak shell temperature for deficiency widths of 0.1 m and 0.5 m was 60-70°C for 13 mm insulation thickness and 160°C for 100 mm insulation thickness. The spread in the peak shell temperatures with insulation thickness is most likely due to the view factors between the shell and the hot jacket being reduced for the thicker insulation. This effect is most evident for small deficiencies. The large change in temperature with deficiency width indicates that 2-D conduction along the wall between the cooler regions under the insulation and the hot regions under the deficiency has a significant effect on deficiency widths below 0.5 m. The simulations also indicate that the maximum difference in peak shell temperature with deficiency width occurs at approximately 20 minutes.

For deficiency widths of 0.5 m or greater, the peak temperature is not affected by the width of the deficiency. This indicates that for deficiency widths greater than 0.5 m the heat transfer in the centre of the deficiency is 1-D.

Results indicate that the lading view factor only had a slight affect on the peak shell temperature, the lower the lading view factor the higher the peak temperature. This small difference results from the fact that the field of view not being taken up by the lading is taken up by the wall, which is not significantly above the lading temperature. The temperature difference was greater for the 12.5 mm insulation since the insulated shell temperature for this thinner insulation is correspondingly higher.

### 3.2 Deficiency Spacing

The effect of adjacent deficiencies was evaluated by calculating the steady state equilibrium temperatures in the tank wall for a range of deficiency sizes and distances between adjacent deficiencies. The model configuration described in Figure 1 is still applicable since the insulated vertical wall on the left hand side of the schematic simply becomes a second line of symmetry.

Initial conditions applied to the simulations are given in Table 5. For the steady state simulations the temperature of the interior wall that was viewed by  $F_w$  was assumed to be constant at the equilibrium shell temperature for a wall with no deficiencies.

**Table 5: Conditions of simulations for gap spacing**

Parameter	Value
Fire temperature	816°C
Grid spacing	fine
Inner shell temperature for $F_w$	0.0125 m insul 91°C 0.10 m insul 201°C
Spacing between adjacent deficiencies	0.1 - 2 m

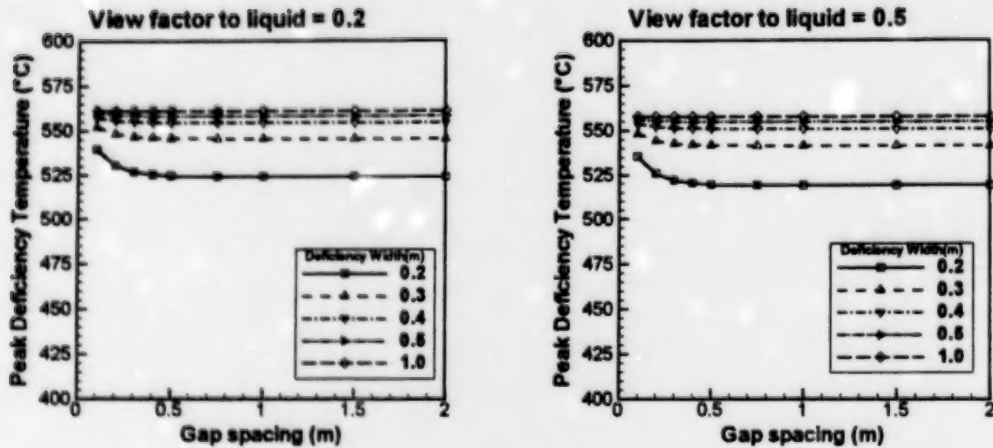


Figure 8: Effect of deficiency spacing on peak shell temperature in deficiency, insulation thickness = 13 mm

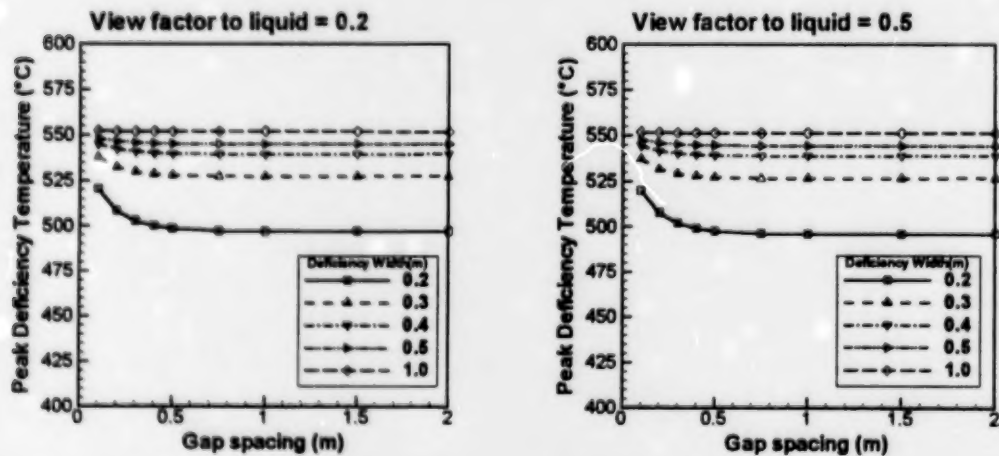


Figure 9: Effect of deficiency spacing on peak shell temperature in deficiency, insulation thickness = 100 mm

The results of the analysis are summarized in Figure 8 and Figure 9 which show the peak equilibrium shell temperature in the deficiency for a range of deficiency sizes and deficiency spacing. The results show that for deficiencies greater than 0.5 m in width, the increase in the peak temperature due to deficiency spacing is less than 4°C. This agrees with the results found for the transient analysis that the heat transfer is 1-D for deficiency widths 0.5 m or greater.

For all deficiency widths the effect of adjacent deficiencies on the peak temperature in the deficiencies is negligible if the spacing between deficiencies is greater than 0.5 m. However, for small deficiencies there can be a significant increase in the peak deficiency shell temperature. For the case of a 20 cm deficiency for a 13 mm insulation

thickness, the peak shell temperature for a deficiency spacing of 10 cm is 15°C greater than for an isolated deficiency. The view factor had very little effect on the peak temperatures for the same reasons described in Section 3.1.

Figure 10 shows the temperature profile along the tank shell for a single 0.3 m deficiency as well as 0.3 m deficiencies spaced 0.1 m apart. The figure shows that as well as the peak temperature being greater for adjacent deficiencies, the temperature in the insulated region between the deficiencies is also higher. The overall effect of closely spaced deficiencies is large areas of the shell at elevated temperatures.

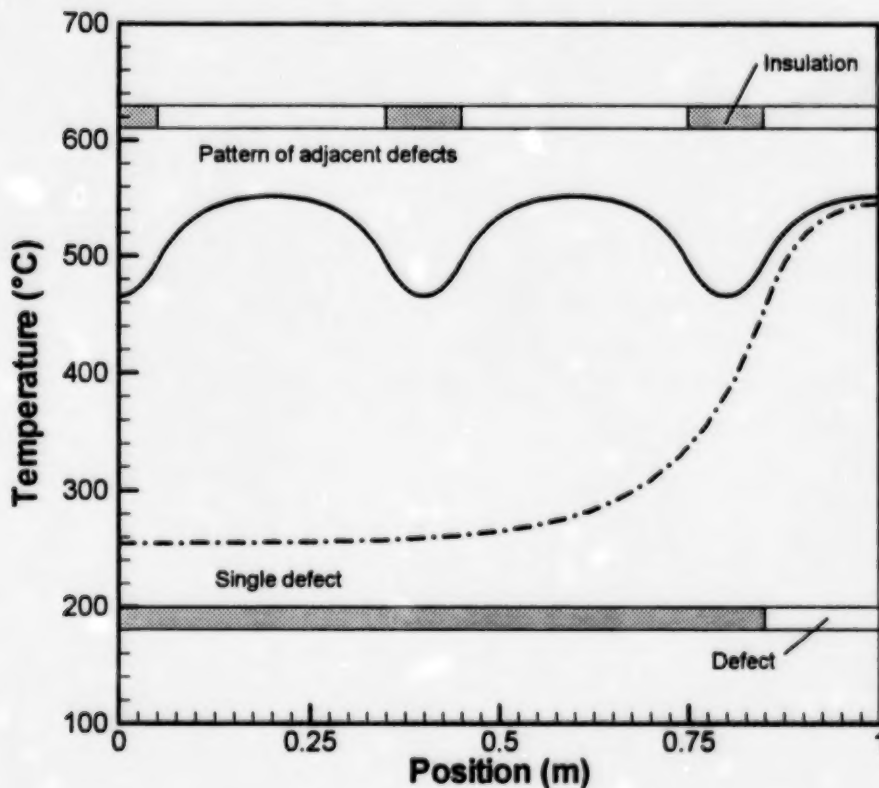


Figure 10: Temperature profiles in tank shell, insulation thickness = 13 mm, lading view factor = 0.2

### 3.3 Model Limitations

In the development of the model some simplifying assumptions were made to reduce the computational requirements. The limitations resulting from these assumptions are outlined in Table 6.

**Table 6 : Model limitations**

Limitation	Comment
2-D	Conduction in the wall is 3-D. By assuming 2-D the predicted temperatures will be higher than in reality. This effect will only be important for small defects.
Constant view factors	The use of two constant view factors does not take into account changing fill levels or variation in temperature in the tank wall.
Wall temperatures for view factors	Using wall temperatures calculated for an insulated wall for radiation calculations in the interior of the tank assumes that the deficiency cannot see itself. This is valid for small deficiencies, but as the size of the deficiency increases the curvature will result in the hot shell under the deficiency being able to see itself. As a result, for large deficiencies the temperatures will be underestimated.

Taking into consideration the above limitations, it is believed that the model is able to capture the general effect of conduction in the wall and the relative effects of deficiency width. Although some quantitative temperatures may be inaccurate due to the assumptions, the relative behaviour of deficiency widths is modeled correctly.

#### **4 Conclusions**

A two dimensional heat transfer analysis of a insulation deficiency in an insulated wall has been completed. Based on the results of the study the following conclusions can be made:

1. The peak shell temperature is not affected by two dimensional heat transfer effects when the deficiency is greater than 0.5 m in width. This includes effects from adjacent deficiencies.
2. Below a width of 0.5 m, the peak temperature in single defects can be significantly lower, up to 100°C in some cases.
3. When several deficiencies are in close proximity with each other, the peak temperature in the deficiency can be increased by 20°C for deficiency widths below 0.5 m.



## 5 References

1. Birk, A.M., Cunningham, M "Field Detection of Tank Car Insulation Deficiencies", Transport Canada Report to be published.
2. Siegel, R., Howell, J, *Thermal Radiation Heat Transfer*, Taylor and Francis, Washington, 1992.
3. Incropera, F., DeWitt, D, *Fundamentals of Heat and Mass Transfer*, John Wiley and Sons, New York, 1996.

## **Appendix I: Surface Emissivity**

## ii) surface emissivity of tank steel

In this analysis it will be assumed that the steel surface has an average emissivity of 0.9. This value is not the same as that used in the AFFTAC code where the emissivity is assumed to be 0.8. It is the opinion of the authors of this report that this value is low and should be closer to 0.9. A low surface emissivity reduces the heat transfer from the fire to the tank. Therefore it should be noted that using 0.8 is not a conservative assumption.

The following data illustrates this.

from Hottel and Sarofim

sheet steel, rough oxide layer	0.8
steel plate, rough	0.94 - 0.97
white enamel fused on iron	0.90
black or white lacquer	0.8 - 0.95
flat black lacquer	0.96 - 0.98
candle soot	0.95

Based on the above list it appears a conservative assumption for emissivity would be 0.9-0.95.

**Appendix J: Radiation View Factor In Vapour Space**

## Discussion of Vapour Space Heat Transfer

At temperatures above 400°C the strength of steel decreases rapidly. A 112W340 tank with internal pressure at the PRV set pressure (around 2.0 MPa) will burst when the wall temperature reaches about 620-640°C. Therefore the problem of predicting tank failure becomes one of determining if and how fast the vapour space wall temperature reaches 620°C.

It will be shown that small changes in heat transfer assumptions can have a dramatic effect on the time it takes for the wall to achieve this critical temperature.

One of the most important factors is the cooling effect of the liquid and vapour lading on the inside of the tank shell. The cooling is by convection and radiation. At high temperatures the radiation will dominate and therefore we will only consider radiation here. Ignoring convection the vapour space is a conservative assumption.

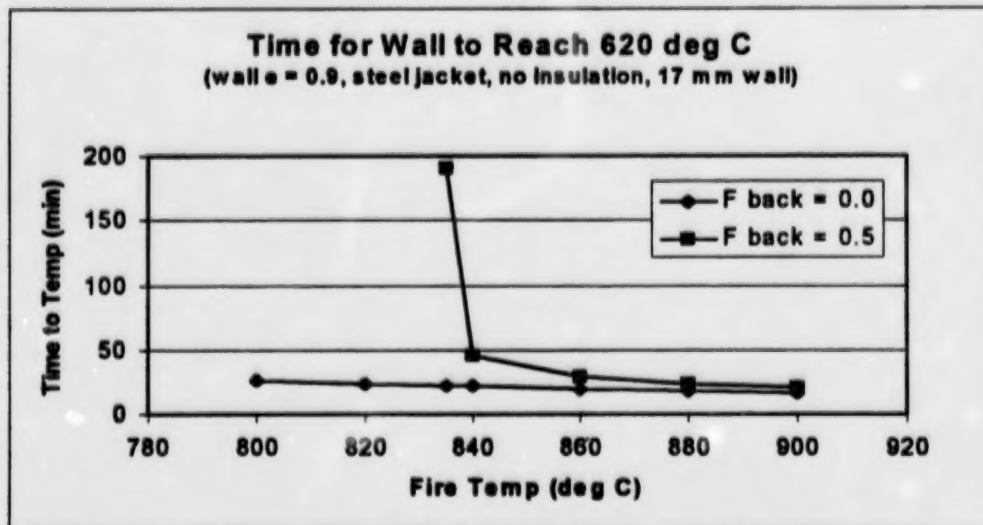


Figure 1: Effect of Vapour Space View Factor on Predicted Wall Temperature

First we will use the AFFTAC assumption that the propane vapour does not absorb thermal radiation. This means the vapour space wall only sees the cool liquid and itself. If the wall sees cool liquid then the wall temperature will be less than if the wall only sees hot wall. This is illustrated in Figure 1.

The figure shows the time to reach 620 deg C as a function of fire temperature for two different inside wall cooling conditions. If the radiation view factor  $F$  from the inside wall to the cool liquid lading is 0.5 (this simulates a tank fill level of greater than 50%) then the wall will be cooled by the liquid and vapour lading (assumed to be at 60 deg C). If the view factor is  $F = 0.0$  (simulates a liquid empty tank) then the wall is radiatively isolated from the lading and it only radiates to itself (assumed to be hot). As can be seen

from the figure this single assumption dramatically alters the outcome. For the well cooled case (high fill condition) the wall will never achieve 620 deg C if the fire is at less than 830 deg C. On the other hand, the uncooled wall (low fill condition) will quickly reach 620 deg C no matter what the fire temperature is.

The AFFTAC model calculates the view factor from the wall to the liquid as follows:

$$F = \frac{A_{\text{liquid}}}{A_{\text{vapour wall}}}$$

where

$A_{\text{liquid}}$  = area liquid surface

$A_{\text{vapour wall}}$  = area of vapour space wall

This is an approximation but is considered to be a reasonable approach. It gives a good average view factor for the vapour space. With the above approach the AFFTAC model calculates  $F = 0.0$  when the tank is empty. When  $F = 0.0$  the wall temperature will continue to rise. Therefore, with the AFFTAC model (for a tank with only steel jacket) the tank will usually fail soon after it is empty if it does not fail earlier. Therefore a critical defect (as far as AFFTAC is concerned) is one that makes the tank empty in less than 100 min.

It should be noted that the above approach does not take into account that the lading vapour will also absorb some of the thermal radiation. It has been crudely estimated (based on data for Methane, see Hottel and Sarofim) that the vapour could absorb as much as 50% of the thermal radiation from the wall. This of course depends on the commodity being considered. This means the AFFTAC approach should be very conservative.

#### AFFTAC Approach for a Single Hot Spot

If the AFFTAC code were used to model a small defect with the remainder of the tank thermally protected the AFFTAC code would not predict failure within 100 minutes because it would take much longer than 100 minutes for the tank to empty.

The AFFTAC code can be used to model this problem by doing the analysis in two steps.

step 1: use AFFTAC to model an insulated and jacketed tank to determine

- time to fail
- time to empty
- variation in liquid level with time



Use the above data to determine heat transfer environment for hot spot in vapour space wall.

step 2: based on data from step 1, estimate hot spot T vs time

- assume failure when hot spot  $T = 620$  deg C
- assume that a defect is present in the vapour space wall
- assume defect does not change overall tank response

Assuming a 112 type car with mineral wool insulation and a steel jacket the time to empty will be approximately 170 minutes. At 100 minutes the tank is still 50% full suggesting considerable cooling effect to the vapour space wall. Assuming a  $815^{\circ}$  C fire (1500 F), and a surface emissivity of 0.8, then no small defect needs to be repaired.

As stated earlier AFFTAC model will show tank failure in 100 minutes or less if tank is empty in 100 minutes or less. This would require a very large defect (of the order of 50% of the tank surface).

## **Appendix K: Pressure Relief Valve Requirements**

## **Appendix L: Pressure Relief Valve Requirements**

From CGSB E43-147 Aug 1997

### **§ 79.15 Pressure Relief Devices**

Except for Class 106, 107, 110, AAR 204W and 113 tank cars, tanks must have a pressure relief device made of material compatible with the lading, that conforms to the following requirements:

(a) **Performance Standard.** Each tank must have a pressure relief system having sufficient flow capacity to prevent pressure build-up in the tank to no more than the flow rating pressure of the pressure relief device in fire conditions as defined in Appendix A of the AAR Specification for Tank Cars.

(b) **Settings for Pressure Relief Devices.**

(1) A reclosing pressure relief valve must have a minimum start-to-discharge pressure equal to the sum of the static head and gas padding pressure and the lading vapour pressure at the following reference temperatures:

(i) 46°C (115°F) for non-insulated tanks;

(ii) 43°C (110°F) for tanks having a thermal protection system incorporating a metal jacket that provides an overall thermal conductance at 15.5°C (60°F) of no more than 10.22 kJ/h·m<sup>2</sup>·°C (0.5 Btu/h·ft<sup>2</sup>·°F) temperature differential; and

(iii) 41°C (105°F) for insulated tanks.

(2) The start-to-discharge pressure of a pressure relief device may not be lower than 5.17 bar (75 psig) or exceed 33% of the minimum tank burst pressure except that tanks built prior to October 1, 1997 having a minimum tank burst pressure of 34.47 bar (500 psig) or less may be equipped with a reclosing pressure relief valve having a start-to-discharge pressure of not less than 14.5% of the minimum tank burst pressure but no more than 33% of the minimum tank burst pressure.

(c) **Flow Rating of Pressure Relief Devices.**

(1) The total flow capacity of each reclosing and non-reclosing pressure relief device must conform to Appendix A of the AAR Specifications for Tank Cars.

(2) The manufacturer of any reclosing or non-reclosing pressure relief device must design and test the device in accordance with Appendix A of the AAR Specifications for Tank Cars.

(3) The flow rating pressure must be 110% of the start-to-discharge pressure for tanks having a minimum tank burst pressure greater than 34.47 bar (500 psig) and from 110 to 130% for tanks having a minimum tank burst pressure less than or equal to 34.47 bar (500 psig).

**(d) Testing Reclosing Pressure Relief Valves.**

(1) The tolerance for the start-to-discharge pressure for a reclosing pressure relief valve is  $\pm 3$  psi for valves with a start-to-discharge pressure of 6.98 bar (100 psig) or less and  $\pm 3\%$  for valves with a start-to-discharge pressure greater than 6.98 bar (100 psig).

(2) The vapour-tight pressure of a reclosing pressure relief valve must be at least 80% of the start-to-discharge pressure.

**(e) Combination Pressure Relief Systems.** A non-reclosing pressure relief device may be used in series with a reclosing pressure relief valve. The pressure relief valve must be located outboard of the non-reclosing pressure relief device.

(1) When a breaking pin device is used in combination with a reclosing pressure relief valve, the breaking pin must be designed to fail at the start-to-discharge pressure specified in par. (b) of this section, and the reclosing pressure relief valve must be designed to discharge at no greater than 95% of the start-to-discharge pressure.

(2) When a rupture disc is used in combination with a reclosing pressure relief valve, the rupture disc must be designed to burst at the start-to-discharge pressure specified in par. (b) of this section, and the reclosing pressure relief valve must be designed to discharge at no greater than 95% of the start-to-discharge pressure. A device must be installed to detect any accumulation of pressure between the rupture disc and the reclosing pressure relief valve. The detection device must be a needle valve, trycock, or tell-tale indicator. The detection device must be closed during transportation.

(3) The vapour-tight pressure and the start-to-discharge tolerance is based on the discharge setting of the reclosing pressure relief device.

**(f) Non-reclosing Pressure Relief Device.** In addition to par. (a) and (c) of this section, a non-reclosing pressure relief device must conform to the following requirements:

(1) Until October 1, 1998, a non-reclosing pressure relief device must incorporate a rupture disc designed to burst at a pressure no less than 100% of the tank test pressure but no more than 33% of the tank burst pressure. After that date, a non-reclosing pressure relief device must incorporate a rupture disc designed to burst at 33% of the tank burst pressure.

(2) The approach channel and the discharge channel may not reduce the minimum flow capacity of the pressure relief device.

(3) The non-reclosing pressure relief device must be designed to prevent interchange with other fittings installed on the tank car, must have a structure that encloses and clamps the rupture disc in position (preventing any distortion or damage to the rupture disc when properly applied), and must have a cover, with suitable means of preventing misplacement, designed to direct any discharge of the lading downward.

(4) The non-reclosing pressure relief device must be closed with a rupture disc that is compatible with the lading and is manufactured in accordance with Appendix A of the AAR Specifications for Tank Cars. The tolerance for a rupture disc is +0 to -15% of the burst pressure marked on the disc.

(g) Location of Relief Devices. Each pressure relief device must communicate with the vapour space above the lading as near as practicable on the longitudinal center line and center of the tank.

(h) Marking of Pressure Relief Devices. Each pressure relief device and rupture disc must be permanently marked in accordance with the Appendix A of the AAR Specifications for Tank Cars.



## **Appendix I: Surface Emissivity**

## ii) surface emissivity of tank steel

In this analysis it will be assumed that the steel surface has an average emissivity of 0.9. This value is not the same as that used in the AFFTAC code where the emissivity is assumed to be 0.8. It is the opinion of the authors of this report that this value is low and should be closer to 0.9. A low surface emissivity reduces the heat transfer from the fire to the tank. Therefore it should be noted that using 0.8 is not a conservative assumption.

The following data illustrates this.

from Hottel and Sarofim

sheet steel, rough oxide layer	0.8
steel plate, rough	0.94 - 0.97
white enamel fused on iron	0.90
black or white lacquer	0.8 - 0.95
flat black lacquer	0.96 - 0.98
candle soot	0.95

Based on the above list it appears a conservative assumption for emissivity would be 0.9-0.95.

## **Appendix J: Radiation View Factor In Vapour Space**

## Discussion of Vapour Space Heat Transfer

At temperatures above 400° C the strength of steel decreases rapidly. A 112W340 tank with internal pressure at the PRV set pressure (around 2.0 MPa) will burst when the wall temperature reaches about 620-640° C. Therefore the problem of predicting tank failure becomes one of determining if and how fast the vapour space wall temperature reaches 620° C.

It will be shown that small changes in heat transfer assumptions can have a dramatic effect on the time it takes for the wall to achieve this critical temperature.

One of the most important factors is the cooling effect of the liquid and vapour lading on the inside of the tank shell. The cooling is by convection and radiation. At high temperatures the radiation will dominate and therefore we will only consider radiation here. Ignoring convection the vapour space is a conservative assumption.

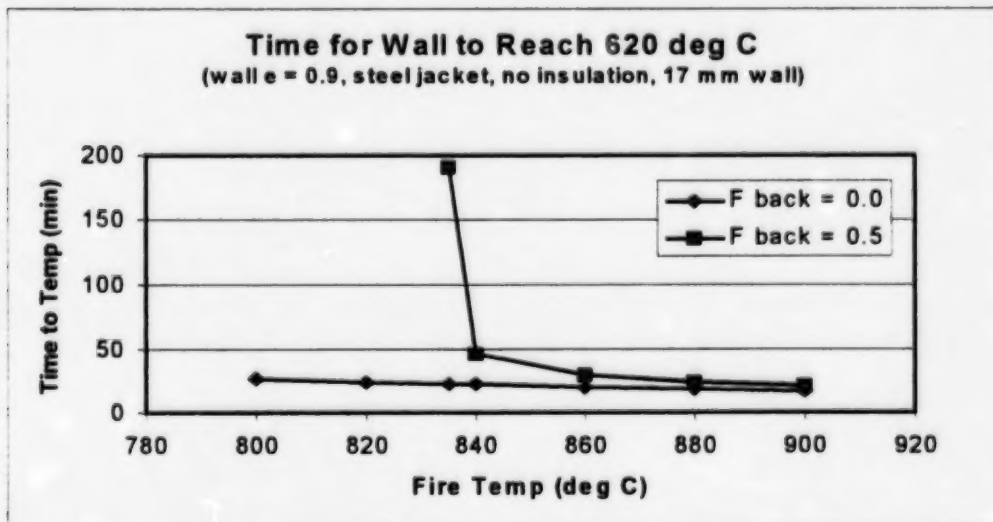


Figure 1: Effect of Vapour Space View Factor on Predicted Wall Temperature

First we will use the AFFTAC assumption that the propane vapour does not absorb thermal radiation. This means the vapour space wall only sees the cool liquid and itself. If the wall sees cool liquid then the wall temperature will be less than if the wall only sees hot wall. This is illustrated in Figure 1.

The figure shows the time to reach 620 °C as a function of fire temperature for two different inside wall cooling conditions. If the radiation view factor  $F$  from the inside wall to the cool liquid lading is 0.5 ( this simulates a tank fill level of greater than 50%) then the wall will be cooled by the liquid and vapour lading (assumed to be at 60 °C). If the view factor is  $F = 0.0$  (simulates a liquid empty tank) then the wall is radiatively isolated from the lading and it only radiates to itself (assumed to be hot). As can be seen from the

figure this single assumption dramatically alters the outcome. For the well cooled case (high fill condition) the wall will never achieve 620 °C if the fire is at less than 830 °C. On the other hand, the uncooled wall (low fill condition) will quickly reach 620 °C no matter what the fire temperature is.

The AFFTAC model calculates the view factor from the wall to the liquid as follows:

$$F = \frac{A_{\text{liquid}}}{A_{\text{vapourwall}}}$$

where

$A_{\text{liquid}}$  = area liquid surface

$A_{\text{vapourwall}}$  = area of vapour space wall

This is an approximation but is considered to be a reasonable approach. It gives a good average view factor for the vapour space. With the above approach the AFFTAC model calculates  $F = 0.0$  when the tank is empty. When  $F = 0.0$  the wall temperature will continue to rise. Therefore, with the AFFTAC model (for a tank with only steel jacket) the tank will usually fail soon after it is empty if it does not fail earlier. Therefore a critical defect (as far as AFFTAC is concerned) is one that makes the tank empty in less than 100 min.

It should be noted that the above approach does not take into account that the lading vapour will also absorb some of the thermal radiation. It has been crudely estimated (based on data for Methane, see Hottel and Sarofim) that the vapour could absorb as much as 50% of the thermal radiation from the wall. This of course depends on the commodity being considered. This means the AFFTAC approach should be very conservative.

#### AFFTAC Approach for a Single Hot Spot

If the AFFTAC code were used to model a small defect with the remainder of the tank thermally protected the AFFTAC code would not predict failure within 100 minutes because it would take much longer than 100 minutes for the tank to empty.

The AFFTAC code can be used to model this problem by doing the analysis in two steps.

- step 1: use AFFTAC to model an insulated and jacketed tank to determine
- time to fail
  - time to empty
  - variation in liquid level with time

Use the above data to determine heat transfer environment for hot spot in vapour space wall.

step 2: based on data from step 1, estimate hot spot T vs time

- assume failure when hot spot  $T = 620^{\circ}\text{C}$
- assume that a defect is present in the vapour space wall
- assume defect does not change overall tank response

Assuming a 112 type car with mineral wool insulation and a steel jacket the time to empty will be approximately 170 minutes. At 100 minutes the tank is still 50% full suggesting considerable cooling effect to the vapour space wall. Assuming a  $815^{\circ}\text{C}$  fire ( $1500^{\circ}\text{F}$ ), and a surface emissivity of 0.8, then no small defect needs to be repaired.

As stated earlier AFFTAC model will show tank failure in 100 minutes or less if tank is empty in 100 minutes or less. This would require a very large defect (of the order of 50% of the tank surface).



## **Appendix K: Pressure Relief Valve Requirements**

From CGSB E43-147 Aug 1997

### **§ 79.15 Pressure Relief Devices**

Except for Class 106, 107, 110, AAR 204W and 113 tank cars, tanks must have a pressure relief device made of material compatible with the lading, that conforms to the following requirements:

(a) Performance Standard. Each tank must have a pressure relief system having sufficient flow capacity to prevent pressure build-up in the tank to no more than the flow rating pressure of the pressure relief device in fire conditions as defined in Appendix A of the AAR Specification for Tank Cars.

(b) Settings for Pressure Relief Devices.

(1) A reclosing pressure relief valve must have a minimum start-to-discharge pressure equal to the sum of the static head and gas padding pressure and the lading vapour pressure at the following reference temperatures:

(i) 46°C (115°F) for non-insulated tanks;

(ii) 43°C (110°F) for tanks having a thermal protection system incorporating a metal jacket that provides an overall thermal conductance at 15.5°C (60°F) of no more than 10.22 kJ/h·m<sup>2</sup>·°C (0.5 Btu/h·ft<sup>2</sup>·°F) temperature differential; and

(iii) 41°C (105°F) for insulated tanks.

(2) The start-to-discharge pressure of a pressure relief device may not be lower than 5.17 bar (75 psig) or exceed 33% of the minimum tank burst pressure except that tanks built prior to October 1, 1997 having a minimum tank burst pressure of 34.47 bar (500 psig) or less may be equipped with a reclosing pressure relief valve having a start-to-discharge pressure of not less than 14.5% of the minimum tank burst pressure but no more than 33% of the minimum tank burst pressure.

(c) Flow Rating of Pressure Relief Devices.

(1) The total flow capacity of each reclosing and non-reclosing pressure relief device must conform to Appendix A of the AAR Specifications for Tank Cars.

(2) The manufacturer of any reclosing or non-reclosing pressure relief device must design and test the device in accordance with Appendix A of the AAR Specifications for Tank Cars.

(3) The flow rating pressure must be 110% of the start-to-discharge pressure for tanks having a minimum tank burst pressure greater than 34.47 bar (500 psig) and from 110 to 130% for tanks having a minimum tank burst pressure less than or equal to 34.47 bar (500 psig).

**(d) Testing Reclosing Pressure Relief Valves.**

(1) The tolerance for the start-to-discharge pressure for a reclosing pressure relief valve is  $\pm 3$  psi for valves with a start-to-discharge pressure of 6.98 bar (100 psig) or less and  $\pm 3\%$  for valves with a start-to-discharge pressure greater than 6.98 bar (100 psig).

(2) The vapour-tight pressure of a reclosing pressure relief valve must be at least 80% of the start-to-discharge pressure.

**(e) Combination Pressure Relief Systems.** A non-reclosing pressure relief device may be used in series with a reclosing pressure relief valve. The pressure relief valve must be located outboard of the non-reclosing pressure relief device.

(1) When a breaking pin device is used in combination with a reclosing pressure relief valve, the breaking pin must be designed to fail at the start-to-discharge pressure specified in par. (b) of this section, and the reclosing pressure relief valve must be designed to discharge at no greater than 95% of the start-to-discharge pressure.

(2) When a rupture disc is used in combination with a reclosing pressure relief valve, the rupture disc must be designed to burst at the start-to-discharge pressure specified in par. (b) of this section, and the reclosing pressure relief valve must be designed to discharge at no greater than 95% of the start-to-discharge pressure. A device must be installed to detect any accumulation of pressure between the rupture disc and the reclosing pressure relief valve. The detection device must be a needle valve, trycock, or tell-tale indicator. The detection device must be closed during transportation.

(3) The vapour-tight pressure and the start-to-discharge tolerance is based on the discharge setting of the reclosing pressure relief device.

**(f) Non-reclosing Pressure Relief Device.** In addition to par. (a) and (c) of this section, a non-reclosing pressure relief device must conform to the following requirements:

(1) Until October 1, 1998, a non-reclosing pressure relief device must incorporate a rupture disc designed to burst at a pressure no less than 100% of the tank test pressure but no more than 33% of the tank burst pressure. After that date, a non-reclosing pressure relief device must incorporate a rupture disc designed to burst at 33% of the tank burst pressure.

(2) The approach channel and the discharge channel may not reduce the minimum flow capacity of the pressure relief device.

(3) The non-reclosing pressure relief device must be designed to prevent interchange with other fittings installed on the tank car, must have a structure that encloses and clamps the rupture disc in position (preventing any distortion or damage to the rupture disc when properly applied), and must have a cover, with suitable means of preventing misplacement, designed to direct any discharge of the lading downward.

(4) The non-reclosing pressure relief device must be closed with a rupture disc that is compatible with the lading and is manufactured in accordance with Appendix A of the AAR Specifications for Tank Cars. The tolerance for a rupture disc is +0 to -15% of the burst pressure marked on the disc.

(g) Location of Relief Devices. Each pressure relief device must communicate with the vapour space above the lading as near as practicable on the longitudinal center line and center of the tank.

(h) Marking of Pressure Relief Devices. Each pressure relief device and rupture disc must be permanently marked in accordance with the Appendix A of the AAR Specifications for Tank Cars.

## **Appendix L: Outage and Filling Limits**

### **4.3 Outage and Filling Limits**

4.3.1 When filling tanks with liquids, sufficient ullage (outage) must be left to ensure that neither leakage nor permanent distortion of the tank will occur as a result of an expansion of the liquid caused by temperatures likely to be encountered during transportation.

4.3.2 Dangerous goods may not be loaded into the dome of a tank car. If the dome of the tank does not provide sufficient outage, vacant space must be left in the shell to provide the required outage.

4.3.3 Liquids and liquefied gases for which there is no specific outage requirement in § 73.314 through § 73.319 must be so loaded that the minimum outage will be as follows:

(1) 1% of the total capacity of a tank, or compartment thereof, or at least 1% of the total capacity of the tank and dome for tank cars and multi-unit tank car tanks at one of the following reference temperatures:

(a) 46°C (115°F) for uninsulated tanks;

(b) 43°C (110°F) for thermally-protected tanks that have a thermal system that meets the requirement of § 79.18 and provides overall thermal conductance at 16°C (60°F) not exceeding 10.22 kJ/h·m<sup>2</sup>·°C (0.5 Btu/h·ft<sup>2</sup>·°F) temperature differential;

(c) 41°C (105°F) for insulated tanks.

(2) for a material which meets the definition of poisonous by inhalation, the outage must be at least 5% of the total capacity of the tank or compartment at one of the following reference temperatures:

(a) 46°C (115°F) for uninsulated tanks;

(b) 43°C (110°F) for thermally-protected tanks that have a thermal system that meets the requirement of § 79.18 and provides overall thermal conductance at 16°C (60°F) not exceeding 10.22 kJ/h·m<sup>2</sup>·°C (0.5 Btu/h·ft<sup>2</sup>·°F) temperature differential;

(c) 41°C (105°F) for insulated tanks.